DISTRIBUTION AND ELEMENTAL COMPOSITION OF SUSPENDED MATTER IN ALASKAN COASTAL WATERS

by

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1. SUMMARY

1.1 Northeast Gulf of Alaska

The distribution of suspended matter in the northeastern Gulf of Alaska is affected by a number of parameters which combine to form a unique distribution pattern. East of Kayak Island the surface particulate matter distributions are dominated by the discharge of sedimentary material from the coastal streams which drain the Bering, Guyot and Malaspina Glaciers. As this material is discharged into the Gulf, the westward flowing currents quickly deflect it to the west along the coast until it reaches Kayak Island where it is deflected to the southwest and is trapped by a clockwise gyre.

The major source of sedimentary material to the Gulf of Alaska is the Copper River. Once discharged into the Gulf, the suspended material from the Copper River is carried to the northwest along the coast until it reaches Hinchinbrook Island where a portion of the material passes into Prince William Sound and the remaining material is carried to the southwest along the coast. of Montague Island.

In general, concentrations of suspended matter in the northeast Gulf of Alaska are high at the surface with an average concentration of approximately 1.0 mg/L. Beneath the surface, concentrations generally decrease with depth until the sea floor is approached. Close to the sea floor suspended matter concentrations increase sharply and the highest concentrations are found within 5 meters of the seawater-aediment interface. Studies of the temporal variability of suspended matter near the bottom show evidence for resuspension and redistribution of bottom sediments. These processes have occurred as a result of interactions between tidal and storm-induced bottom currents and the surficial sediments.

Studies of the chemical composition of the suspended matter show significant spatial and seasonal variations which have been correlated with seasonal variations in primary productivity, variations in the supply and transport of terrestrially derived suspended matter from the coastal rivers, and resuspension of bottom sediments.

1.2 Lower Cook Inlet

The seasonal distributions and elemental compositions of suspended particulate matter in lower Cook Inlet were studied and compared with current patterns and bottom sediment distributions. In general, the suspended matter distributions appear to follow the pattern of circulation in lower Cook Inlet and Shelikof Strait. The inflowing clear saline Gulf of Alaska water, which is enriched in biogenic particles of marine origin, flows northward along the eastern coast until it reaches the region near Cape Ninilchik where it mixes with the outflowing brackish water. The outflowing turbid water, which contains terrigenous particles derived primarily from the Susitna, Matanuska, and Knik Rivers, moves seaward along the western side of the inlet past Augustine Island and Cape Douglas into Shelikof Strait where it mixes with the oceanic water and is dispersed. Chemical analysis of the particulate matter reveals that: (1) fine-grained aluminosilicate minerals generally comprise about 80-95% of the suspended matter with biogenic material making up the rest; (2) Kachemak Bay is characterized by trace element enrichments in the organic phases of the particulate matter; (3) Kalgin Island region is characterized by trace element enrichments in the Fe-Mn oxyhydroxide phases; and (4) lower Cook Inlet and Shelikof Strait are linked by biogeochemical processes involving Mn and organic matter. These studies lead to the speculation that bioaccumulation of certain trace elements could occur in Kachemak Bay if it were to receive a sudden massive insult of these dissolved trace elements.

1.3 The Southeastern Bering Sea Shelf

The distribution of suspended matter at the surface in the southeastern Bering Sea Shelf is controlled by the discharge of sedimentary material from the coastal rivers and the semi-permanent counterclockwise currents which dominate the water circulation in Bristol Bay. A large plume of suspended matter extends to the southwest from Cape Newenham. Suspended matter originating from the Kvichak and Nushagak Rivers is carried to the west until it reaches Cape Newenham where it combines with a portion of the material discharged from the Kuskokwim River and is deflected to the southwest. Chemical analysis of suspended matter from the plume indicates that it is essentially of terrestrial origin.

A second plume extends to the southwest from Kuskokwim Bay. High concentrations of suspended matter extend as far west as Nunivak Island. This material is derived from the Kuskokwim River.

Along the Alaska Peninsula surface suspended matter concentrations decrease rapidly away from the coast. As the Pacific Ocean water passes through Unimak Pass and is deflected to the northeast along the coast of the Alaska Peninsula, suspended matter of marine origin is carried into Bristol Bay. When this water mixes with the highly turbid Shelf water, it is rapidly diluted producing the sharp gradients in the suspended matter distributions near the coast.

In the region north of Unimak Pass large suspended matter plumes appear to be the result of increased productivity during the summer months.

Below the surface, the particulate matter distributions follow the same distribution pattern as at the surface. However, suspended matter concentrations increase sharply near the bottom indicating that resuspension of bottom sediments is occurring.

Studies of the major and trace element composition of the suspended matter show significant spatial variations which are directly related to the supply of terrestrially derived suspended matter from coastal rivers and local variations in primary productivity.

1.4 Norton Sound

The distributions and elemental compositions of suspended particulate matter in Norton Sound were studied and compared with current patterns and sediment distributions. The suspended matter distributions appear to follow the general pattern of cyclonic circulation in the Sound. The inflowing water picks up terrigenous aluminosilicate material from the Yukon River and transports it to the north and northeast around the inside periphery of the Sound, with some material settling to the bottom and the remaining ❑aterial being transported to the northwest through the Bering Strait into the Chukchi Sea. Chemical analysis of the suspended material from Norton Sound reveals that: (1) aluminosilicate material from the Yukon River comprises about 88-92% of the suspended matter, with biogenic matter making up the rest; (2) organic matter of terrestrial origin dominates the organic phase in the Yukon River Estuary; and (3) Mn and Zn are enriched in an oxyhydroxide phase of the surface and near-bottom suspended matter in Norton Sound.

2. INTRODUCTION

The development of petroleum and natural gas resources on the Alaskan outer continental shelf will undoubtedly result in an increased potential for crude oil contamination of its coastal waters. Of particular concern are the ❑ajor accidents which cause massive oil spills , such as the ARGO MERCHANT oil spill on Fishing Rip near Nantucket (NOAA Special Report, 1977). However,

chronic release of oil through minor spills and localized transfer operations may be more important over the long term.

Oil spilled onto the surface of the ocean is acted upon by several physical processes, including evaporation, solution, emulsification, and injection into the atmosphere (Kreider, 1971; McAuliffe, 1966, 1969, and Baier, 1970). With respect to the oceanic environment, only the solution and emulsification processes represent important mechanisms by which spilled oil becomes entrained in the water column, thus increasing its potential for impacting marine organisms.

Since crude oil is sparingly soluble in seawater, it tends to form emulsions when introduced into marine waters, especially under intense wave action. The emulsions have a high affinity for particles and tend to be adsorbed rapidly. Recent studies of oil spills in coastal waters containing high suspended loads have indicated rapid dispersal and removal of the oil by sorption onto particles along frontal zones (Forrester, 1971; Kolpack, 1971; and Klemas and Polis, 1977). These zones are regions where turbid brackish water contacts seawater. At the interface downwelling occurs in most cases, causing the inorganic material from the rivers and any associated contaminants to be carried down into the water column. Similarly, laboratory studies involving the interaction between Prudhoe Bay and Cook Inlet crude oils and river-derived inorganic suspended matter have indicated that significant amounts of oil may be accommodated by suspended material, and that the quantity of oil retained on the particles is dependent upon the isoelectric point of oil and sediment particles, particle size, temperature, and the concentration of oil relative to that of the suspended material (Feely et al., 1978). Since these processes play a major role in the dispersal and deposition of

petroleum hydrocarbons, this report addresses the spatial and temporal variations of the distribution, chemical composition, and dispersal of suspended material in several continental shelf regions of Alaska.

3. CURRENT STATE OF KNOWLEDGE

3.1 Northeast Gulf of Alaska

Reimnitz (1966) studied the sedimentation history and lithology of sediments from the Copper River Delta. He estimated the particulate matter supply of the Copper River to be 107 x 10^6 tons/yr which mostly consists of fine-grained sands and silt.

Sharma et al. (1974) compared some surface particulate matter distributions taken during February 24-28, 1973, between Kenai Peninsula and Kayak Island with ERTS multispectral scanner images of the same region which were obtained on October 12, 1972, and August 14, 1973. The ERTS images show that the Copper River and Bering Glacier provide most of the sediment load to this region. The westward flowing current deflects a portion of the Copper River plume to the west. The suspended matter moves along the coast with some material entering Prince William Sound through the passages on either side of Hinchinbrook Island and the remaining material is carried along the southeast shore of Montague Island.

Carlson et al. (1975) used ERTS imagery to study the transport of suspended material in nearshore surface waters of the Gulf of Alaska. During the late summer and early fall months large quantities of fine-grained silt and clay-sized material from the Bering, Guyot and Malaspina Glaciers are discharged into the Gulf between Kayak Island and Yakutat Bay. This material is carried to the west by the Alaska current until it reaches Kayak Island where it ia deflected to the south.

El Wardani (1960) studied the distribution of organic P in the Bering Sea, Aleutian trench and the Gulf of Alaska. He demonstrated that particulate organic P in the upper 200 meters of the water column bears an inverse relationship to inorganic P. Below 200 meters no detectable particulate organic P was found.

3.2 Lower Cook Inlet

Previous studies of suspended material in lower Cook Inlet have been limited to observations of LANDSAT satellite and aircraft photographs, augmented with sea-truth measurements in some places. These studies have provided useful information about near-surface suspended matter dispersal patterns, particularly in the Kalgin Island region where concentration gradients have been observed to be extremely high. Sharma, Wright, Burns, and Burbank (1974) used these techniques to study suspended matter distributions in Cook Inlet during late summer of 1972 and early spring of 1973. Suspended matter concentrations ranged from 100 mg/L near the Forelands to 1-2 mg/L near the entrance of the inlet. Large temporal variations were related to tidal variations in water circulation.

Gatto (1976) studied the dispersal of sediment plumes from coastal rivers as affected by tidal currents in the inlet. Turbid plumes from the Tuxedni, Drift, Big, and McArthur Rivers on the west side formed distinct surface layers, riding over and mixing with the saline water from the south. During flood tide, the plumes flowed northward along the coast. On ebb tide, the plumes migrated back to the south and west. Occasionally, the relict plumes were observed far offshore, which indicated that at least some plumes of sediment-laden water were capable of ❑aintaining their identity for several tidal cycles.

Burbank (1977) used LANDSAT imagery to study suspended matter dispersal patterns in Kachemak Bay. Suspended material in Kachemak Bay is derived from the inorganic and biogenic materials residing in the inflowing saline Gulf of Alaska water, in situ production, and suspended material discharged from the Fox and other local rivers. Sediment plumes were observed along the northwest shore of inner Kachemak Bay. These plumes were diverted around Homer Spit and into outer Kachemak Bay by a counter-clockwise rotating gyre. In the outer bay, the plumes moved to the west and north under the influence of a second counterclockwise gyre.

3.3 Southeastern Bering Sea Shelf

There is very little published information about the distribution and composition of suspended particulate matter in the southeastern Bering Sea Shelf.

Sharma et al. (1974) compared some particulate matter distributions taken during June-July 1973 in the southern Bering Sea and Bristol Bay region with ERTS multi-spectral scanner images of the same area which were obtained on October 2, 1972. The surface contours of suspended load distributions indicate several regions of relatively turbid water which originate from a variety of sources. These turbid regions include:

(1) A region of turbid water which is north of the Aleutian Islands. This is probably due to the high level of primary productivity that is the result of the mixing of nutrient-rich deep water with the Alaskan Stream which flows into the Bering Sea from the south.

(2) A region of turbid water which extends south from Kuskokwim Bay and west from northern Bristol Bay. This plume probably represents sus-

pended sediments derived from the Kuskokwim River from the north and the Kvichak and Nushagak Rivers from the east.

(3) A region of slightly turbid water extending to the southwest from Bristol Bay which probably represents suspended matter derived from the Kvichak and Nushagak Rivers.

The ERTS imagery indicates that the Nushagak River is a major source for particulate matter in the Bristol Bay area. The suspended particles from Kvichak and Nushagak Rivers are carried to the west by the prevailing counter-clockwise current. Sharma et al. (1974) state that although the river plumes remain close to shore, offshore transport of material in suspension is probably brought about by tidal currents.

There is only a small amount of information about the chemical composition of the suspended matter in the southeastern Bering Shelf. Loder (1971) studied the distribution of particulate organic carbon (POC) north of Unimak Pass and found high POC concentrations (221-811 μgC/L) in the thermally stabilized upwelled water north of Unalaska Island. Lower POC concentrations were found north of Unimak Island and west of Akutan Pass which presumably were due to current mixing.

Tsunogai et al. (1974) studied the distribution and composition of particulate matter from six stations in the south central and southeastern Bering Sea and northern North Pacific Ocean. They found the highest concentrations of particulate matter occurred at 20 to 30 meters depth which appeared to be due to the high productivity and the slow decomposition of organic matter just below the surface. The organic portion of the suspended matter was about 67 percent for the samples from the Bering Sea and 80 percent for the samples south of the Aleutian Islands in the northern North Pacific.

3.4 Norton Sound

Previous work on suspended matter in Norton Sound has been limited to studies of LANDSAT photographs and suspended matter distributions. Sharma et al. (1974) used density-sliced LANDSAT photographs and sea truth measurements to study suspended matter distributions in Norton Sound during the late summer of 1973. Suspended matter concentrations were highest near the mouth of the Yukon River (range: 2-8 mg/L) and in Norton Bay (range: 3-4 mg/L), located in the northeast corner of the Sound. The authors postulated that the general pattern of cyclonic circulation in the Sound caused suspended material to be transported to the north and northeast along the coast. The authors also noted that unusually high particulate matter concentrations (>9.0 mg/L) were observed throughout the water column in the region approximately 30 km south-southwest of Nome. They suggested that this plume could have been a detached portion of the Yukon River plume which was isolated by tidal pulsation.

Cacchione and Drake (1979) combined suspended matter surveys during September - October 1976 and July 1977 with deployments of a tripod (GEOPROBE) containing instruments designed to measure bottom currents, pressure, temperature, and light transmission and scattering to study suspended matter dispersal patterns in Norton Sound. They described the transport of suspended materials as dominated by distinctly different quiescent and storm regimes. The quiescent regime was characterized by relatively low levels of sediment transport caused by tides and mean flow to the north and northeast, which was augmented by surface waves during spring tides. The authors stated that during this period much of the fine-grained suspended matter present over the prodelta was resuspended at shallow depths during spring tide and transported northward with the mean current. The storm regime, which occurs during the months of September through November, was characterized by strong southerly

and southwesterly winds which generate waves with heights of 1-3 m and periods of 8-11 sec. The storm events cause near-bottom shear velocities which are in excess of that required for resuspension of bottom sediments, and, as a result, more than 50% of the sediment transport occurs during this regime.

Although there is no background information on the chemistry of suspended matter in Norton Sound, extensive studies of trace metal partitioning in various phases of Yukon River materials were conducted by Gibbs (1973; 1977). He concluded that transition metals associated with oxhydroxide coatings and crystalline phases comprised the major fraction (72-91%) of riverine transition metal transport to the sea. Particulate organic phases contained the next largest fraction (3-16% of the total). Metals in solution and metals sorbed to particulate materials made up the remainder (5-15% of the total).

4. THE STUDY REGIONS

4.1 Northeast Gulf of Alaska

The northeast Gulf of Alaska is bordered by a mountainous coastline containing numerous glaciers which deliver large quantities of suspended material to the Gulf during the summer months when maximum discharge occurs (fig. 1). The major sediment discharge is from the Copper River. Reimnitz (1966) estimates that approximately 107 x 10^6 tons of fine-grained material are delivered annually to the Gulf by way of the Copper River system. The maximum discharge of the Copper River occurs during the months of June through September.

Additional inputs into the Gulf occur along the coastline east of Kayak Island where coastal streams containing high sediment concentrations drain the Bering, Guyot and Malaspina Glaciers. Since there are no permanent gauging stations on these streams, there is no information about the quantities of materials that are discharged into the Gulf from these sources.

The current systems in the Gulf are dominated by the large counterclockwise gyre of the Alaska Current. It is usually characterized by a core of relatively warm (5.5° - 6.2°C) water at about 130 meters (Gait and Royer, 1975). The Alaskan Stream comes in contact with the shelf just east of Icy Bay where it is turned to the west and appears to follow the 150 meter isobath.

West of Kayak Island the Alaska Current is deflected to the southwest, leaving the large shelf area between Middleton Island and the Copper River Delta relatively free of its influence. In this region the circulation is affected by seasonal wind patterns. In the summer, the winds are predominantly from the southwest. This produces an Ekman drift of surface waters offshore. During the winter, the winds are from the southeast which results in an Ekman drift onshore and downwelling in subsurface waters.

4.2 Lower Cook Inlet

Cook Inlet is a large tidal estuary in south central Alaska. It lies on a northeast-southwest axis and is about 150 nautical miles long and 50 nautical miles wide at the mouth (fig. 10). Physiographically, the inlet is divided into three sections. At the head of the inlet, it separates into Knik and Turnagain Arms. Near the middle, upper Cook Inlet is separated from lower Cook Inlet by two geographic constrictions, the East and West Forelands.

The inlet receives fresh water from four major rivers: the Matanuska and Knik Rivers at the head of Knik Arm and the Susitna and Beluga Rivers to the northwest. These rivers supply about 70% to 80% of the freshwater input (Rosenberg and Hood, 1967). In addition, numerous streams containing large concentrations of glacial flour drain into the lower inlet from both sides. Included in this category are the Kenai, Kalisof, Nihilchik, and Anchor Rivers

on the eastside and the McArthur, Big, Drift, and Tuxedni Rivers which discharge into the inlet from the west.

Water circulation in lower Cook Inlet has been described by several authors (Kinney et al., 1970; Wright et al., 1973; Gatto, 1976; Burbank, 1977; and Muench et al., 1978). The last reference provides the most completed description of water circulation in lower Cook Inlet. Circulation in the inlet is characterized by a net inward movement of oceanic water up the eastern shore and a net outward movement of a mixture of oceanic water and runoff water along the western shore. In the vicinity of the Forelands, the water masses are vertically mixed due to the turbulent action of tidal currents. However, lateral separation of the water masses is apparent, resulting in a shear zone between the incoming saline water on the east-side and the outgoing less saline water on the west. Coastal upwelling occurs in the vicinity of the Chugach Islands, from the region west of Elizabeth Island to Cape Starichkof.

The distribution and composition of bottom sediments in lower Cook Inlet have been studied (Sharma and Burrell, 1970; Bouma and Hampton, 1976; Hein et al., 1979). The sediments are primarily composed of medium-to-fine grained sands; however, occasional silt and clay-sized sediments have been observed. The deposits in the northern part of the inlet are winnowed Pleistocene-early Holocene gravels, with many of the sand-sized and smaller particles being removed and redeposited to the south. In addition to the relict sands and gravels, the sediments also contain a very thin cover of fine-grained silts and clays which are modern. Hein et al. (1979) state that the clay mineral deposits in lower Cook Inlet are dominated by clay mineral suites from two distinct sources. A chlorite-rich suite dominates the clay mineral fraction in deposits from the region around the Barren Islands in Kachemak Bay. The

Copper River appears to be the major source of this material as it discharges chlorite-rich fine-grained material into the northeast Gulf of Alaska which is diverted to the west and southwest by the coastal alongshore currents (Feely et al., 1979). Apparently, some of this material reaches Kennedy Entrance and is transported into lower Cook Inlet along with the inflowing Gulf of Alaska water.

The region to the west and north of Kachemak Bay is dominated by an illite-rich suite; the Susitna River in upper Cook Inlet being its major source. These authors further state that the distribution of clay minerals in the bottom sediments in lower Cook Inlet reflects the dispersal routes for suspended material in the overlaying water. Thus, fine-grained particles from these two sources follow the general pattern of water circulation in the inlet and form the bulk of the mud deposits in the quiet embayments along the shore and throughout Shelikof Strait.

4.3 Southeastern Bering Sea Shelf

The southeastern Bering Shelf is a relatively shallow embayment which is bounded by the Kilbuk Mountains to the north and east, and the Alaska Peninsula to the south (fig. 8). Except for some small depressions near the Alaska Peninsula, the shelf floor is extremely smooth with an average slope of about 0.0003 (Sharma, 1974).

The region receives sedimentary material from the Kuskokwim, Kvichak, and Nushagak rivers. The largest river, the Kuskokwim, discharges approximately 4.0×10^6 tons of sediments annually (Nelson, 1974). The maximum discharge occurs during the months of May through September.

A counterclockwise movement generally dominates the water motion in the Bristol Bay region. Pacific Ocean water enters the Bering Sea through the

Aleutian Island passes and flows to the northeast along the coast of the Alaska Peninsula. The water moves along the northern coastline by tidal and wind-driven currents until it reaches Nunivak Island where it is turned to the north.

The permanent currents in the southeastern Bering Shelf appear to be somewhat sluggish. Current velocities ranging from 2.0 to 5.0 cm sec^{-1} have been observed north of the Alaska Peninsula (Hebard, 1959). However, tidal currents are dominant in northeastern Bristol Bay where tidal velocities of up to 125 cm sec have been observed in Nushagak Bay (U.S. National Ocean Survey, 1973).

4.4 Norton Sound

Norton Sound is a shallow embayment located in the central region of the west coast of Alaska (fig. 9). Relative to the Bering Sea, it is an east-west extending embayment which is about 200 km long in the east-west direction and about 150 km wide in the north-south direction. The Yukon River, which flows into the southwest quadrant of the embayment, is the major source of freshwater and suspended matter to the Sound as well as to the entire eastern Bering Sea Shelf. Its annual suspended matter load of 88 x 10^6 tons ranks 18th among the major rivers of the world (Inman and Nordstrom, 1971). The annual discharge curve for the Yukon River is unimodal with peak flow occurring during June and low flow conditions persisting throughout the winter months. Additional smaller freshwater inputs into the Sound occur along the coastline east of the Yukon River Delta and along the northern coast.

Water circulation in the vicinity of Norton Sound has been described by several authors (Coachman et al., 1975; Muench and Ahlnäs, 1976; Muench et al., 1981). The shelf water west of Norton Sound, the Alaska Coastal water,

has a net northward flow of about 1.5 x 10^6 m^3 see^{-1}. About one-third of this flow passes between St. Lawrence Island and the mouth of Norton Sound. The intensity of the cyclonic flow appears to be affected by local winds and by freshwater runoff. The eastern half of the Sound is characterized by two vertically well-mixed layers. The lower layer contains cold, dense residual water formed during the previous winter. Both water masses follow the general pattern of cyclonic flow in the' region, although much more sluggishly than surface and bottom waters further to the west.

The distribution of sediments in Norton Sound has been summarized (McManus et al., 1974; Sharma, 1974; Nelson and Creager, 1977; and McManus et al., 1977). In the central and southern regions, the sediments consist of very fine-grained sands and silts which are modern. In the northern region, silty sands predominate everywhere except for a narrow strip along the coast between Cape Nome and Cape Douglas. Here, coarse sands and gravels predominate because bottom currents have caused almost complete erosion of the fine-grained sediments. Approximately one-half to two-thirds of the sediment load of the Yukon River is deposited as a bank of sediments extending from the Yukon River Delta northward and eastward around the inside periphery of the Sound. The remaining sediment load of the Yukon River is transported to the north through the Bering Strait and deposited in the Chukchi Sea.

5. SOURCES, METHODS AND RATIONALE OF DATA COLLECTION

In order to obtain information about the distribution and composition of suspended matter in the various study areas, we have conducted three cruises in the northeast Gulf of Alaska (Cruise RP-4-Di-75C-I, 21 October-10 November 1975; Cruise RP-4-Di-76A-III, 13-30 April 1976; and Cruise RP-4-Di-76B-I, 19-31 July 1976), six cruises in lower Cook Inlet (Cruise RP-4-Di-77A-IV,

4-16 April 1977; Cruise Acona-245, 28 June-12 July 1977; Cruise RP-4-Di-77C-II, 3-12 October 1977; Cruise RP-4-Di-78A-III, 4-17 May 1978; Cruise RP-4-Di-78B-II, 22 August-6 September 1978; and Cruise RP-4-Di-79A-II, 7-20 May 1979), two cruises in the northeastern Bering Sea Shelf (Cruise RP-4-Di-75B-III, 12 September-5 October 1975 and Cruise RP-4-MW-76B-VII, 24 June-9 July 1976), and one cruise to Norton Sound (Cruise RP-4-Di-79A-VI, 7-18 July 1979). Figures 1 through 9 show the locations of the sampling stations for the various" cruises.

5.1 Sampling Methods

5.1.1 Particulate Matter

Water samples were collected from preselected depths in General Oceanics 1070 10-L PVC Top-Drop Niskin bottles. Nominally these depths included: 0-2 m, 10 m, 20 m, 40 m, 60 m, 80 m, and 5 meters above the bottom. Aliquots were drawn within 10-15 minutes after collection from each sample and vacuum filtered through preweighed 0.4 μm pore diameter Nuclepore polycarbonate filters (47 mm) for total suspended matter concentration determinations and 25 mm for multi-element particulate composition analyses. Samples were also filtered through 25 mm, 0.45 μm pore diameter Selas silver filters for particulate C and N analyses. All samples were rinsed with three 10mL aliquots of deionized and membrane filtered water, placed in individual petri dishes with lids slightly ajar for a 24-hour desiccation period over sodium hydroxide, and then sealed and stored (silver filters frozen) for subsequent laboratory analysis.

5.1.2 Nephelometry

The vertical distribution of suspended matter was determined with a continuously recording integrating analog nephelometer. The instrument was

interfaced with the ship's CTD system using the sound velocity channel (14-16 KHZ) . Continuous vertical profiles of forward light scattering were obtained in analog form on a Hewlett Packard 7044 X-Y recorder.

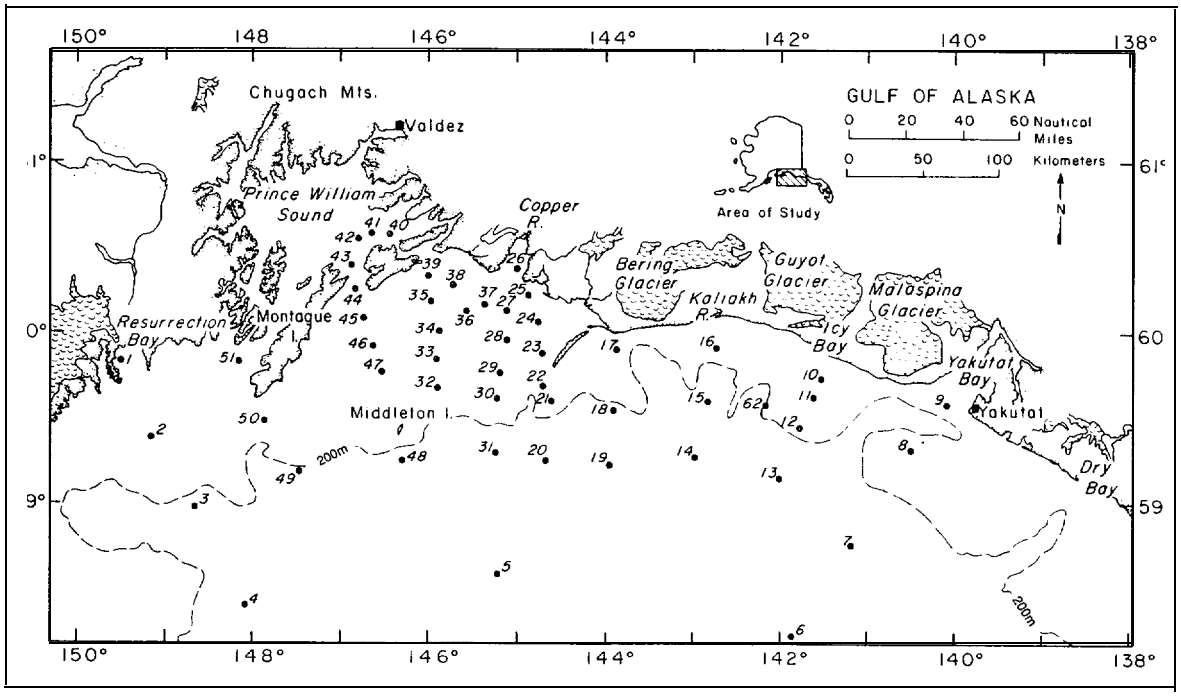

Figure 1. Locations of suspended matter stations in the northeastern Gulf of Alaska (Cruise RP-4-Di-75-C-I, **21** October-10 **November 1975).**

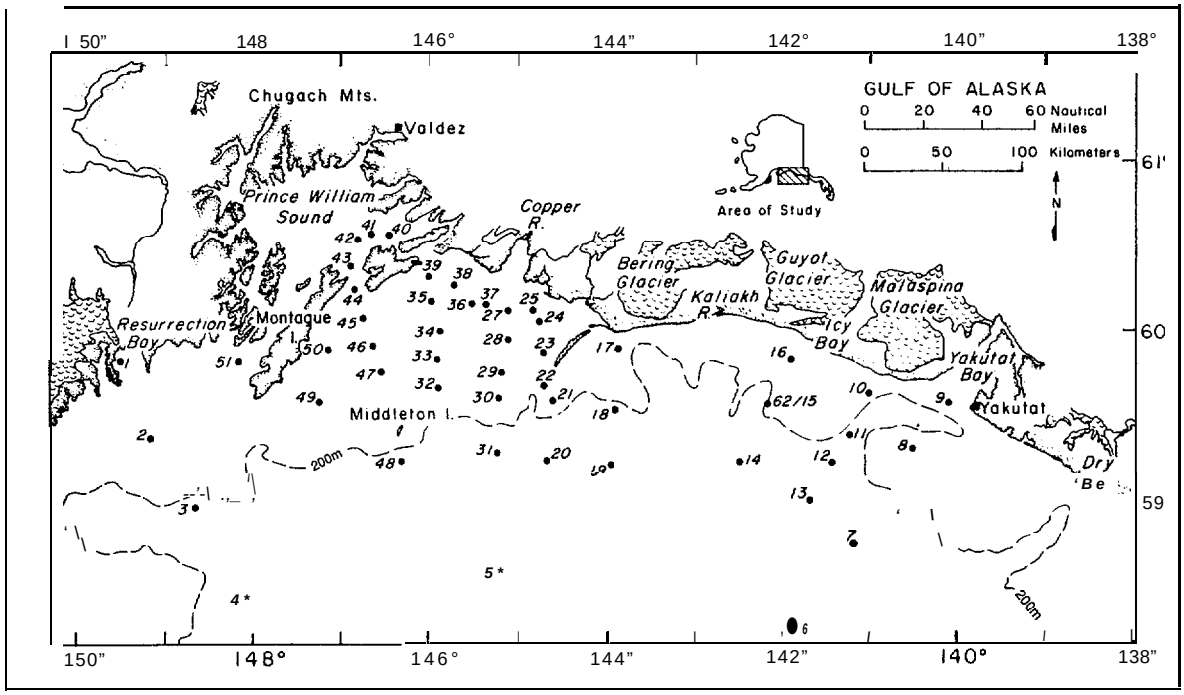

Figure 2. Locations of suspended matter stations in the northeastern Gulf of Alaska (Cruises RP-4-Di-76A-III, 13-30 April 1976 and RP-4-Di-76B-I, 19-31 July 1976).

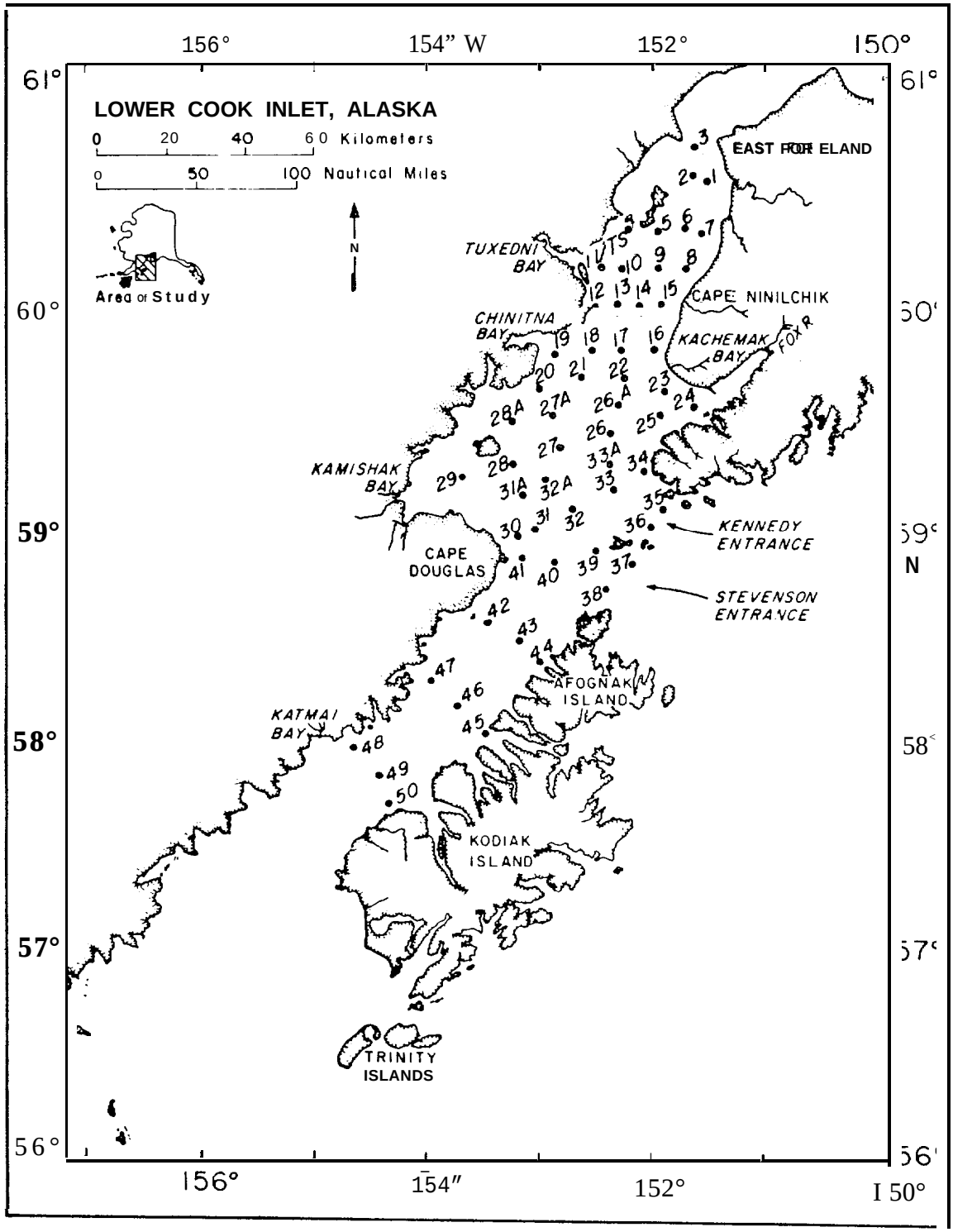

Figure 3. Locations of suspended matter stations in lower Cook Inlet and Shelikof Strait (Cruise RP-4-Di-77A-IV, 4-16 April 1977).

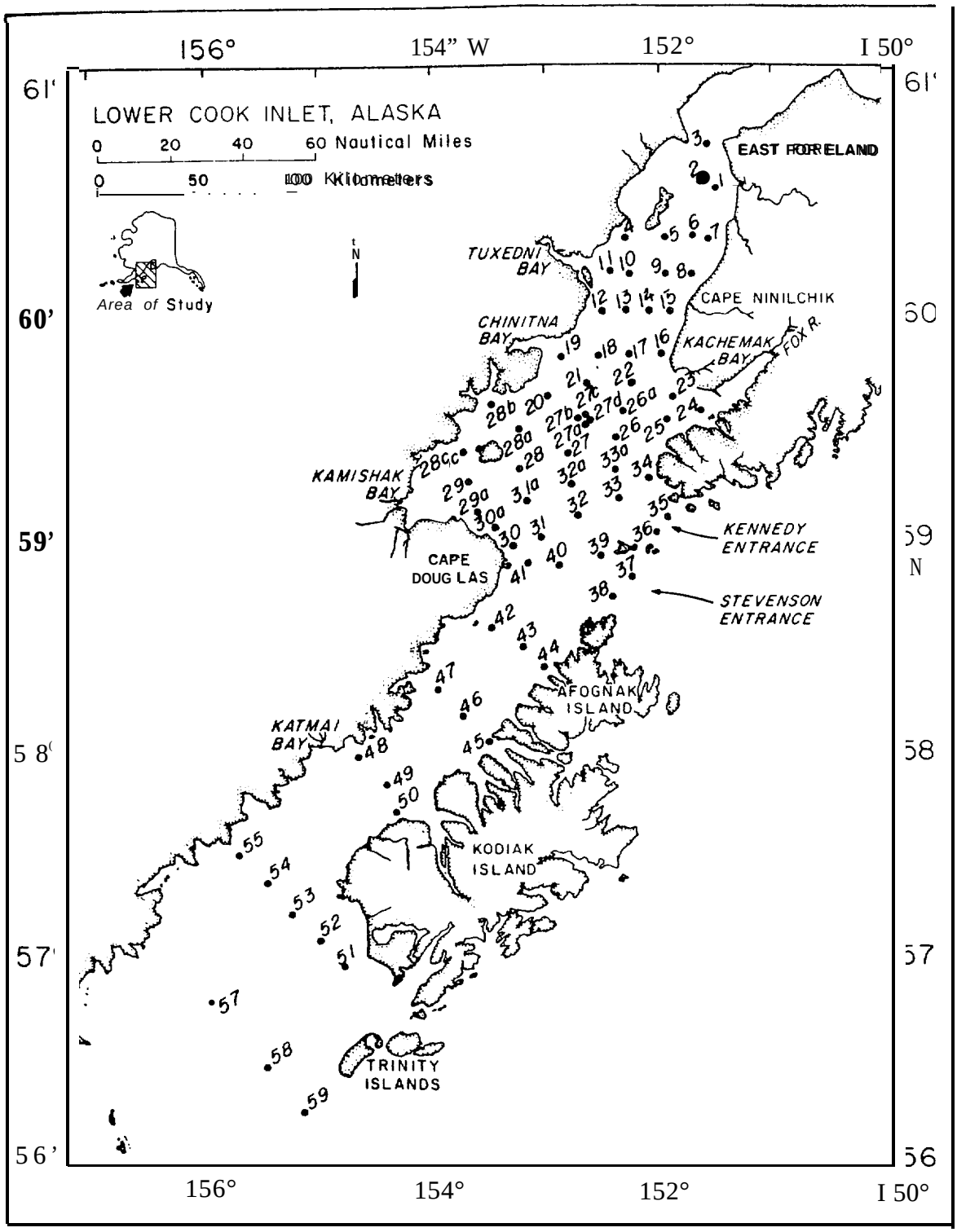

Figure 4. Locations of suspended matter stations in lower Cook Inlet and Shelikof Strait (Cruise Acona-245, 28 June - 12 July 1977) .

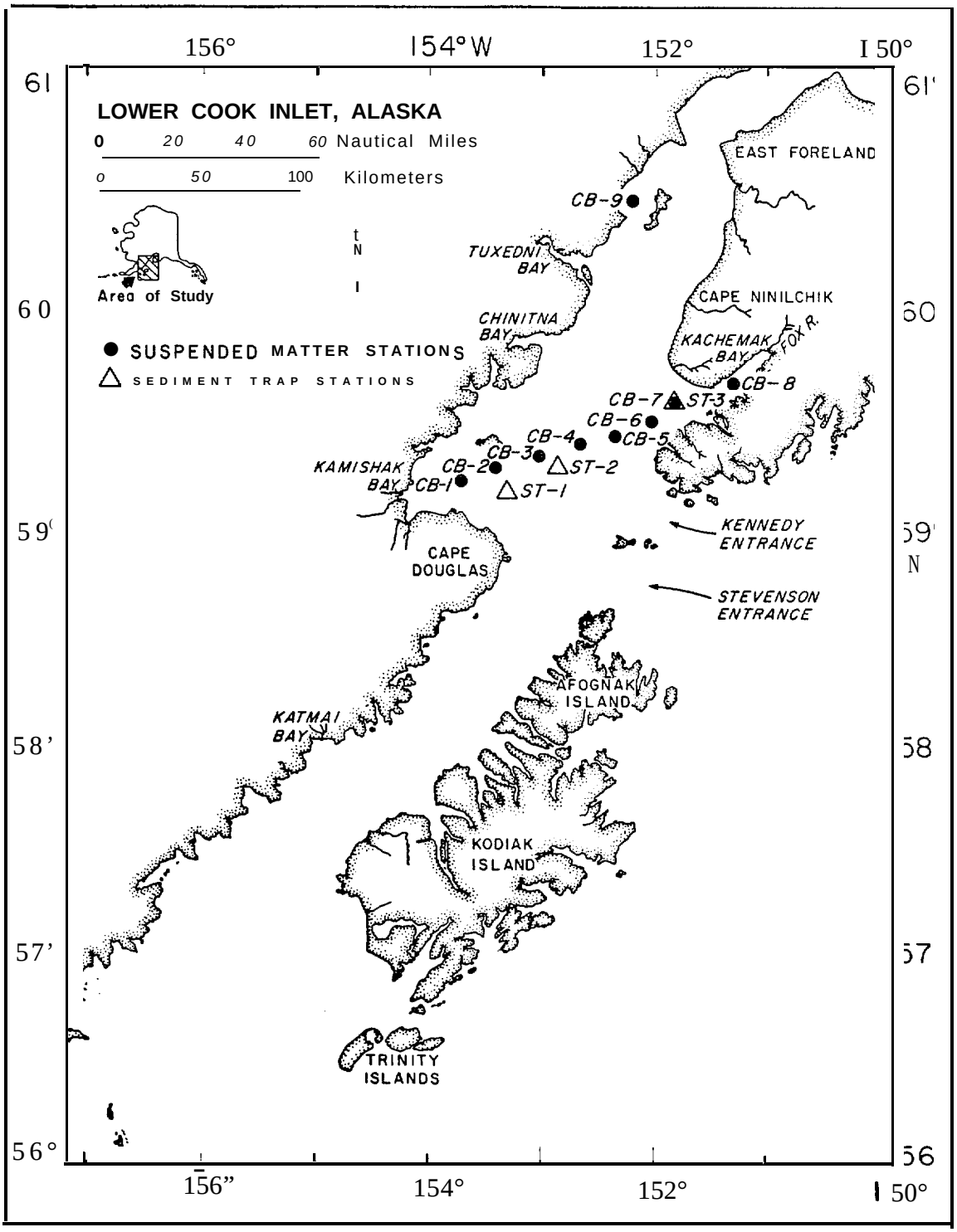

Figure 5. Locations of suspended matter and sediment trap stations in lower Cook Inlet (Cruise RP-4-Di-78A-III, 4-17 May 1978).

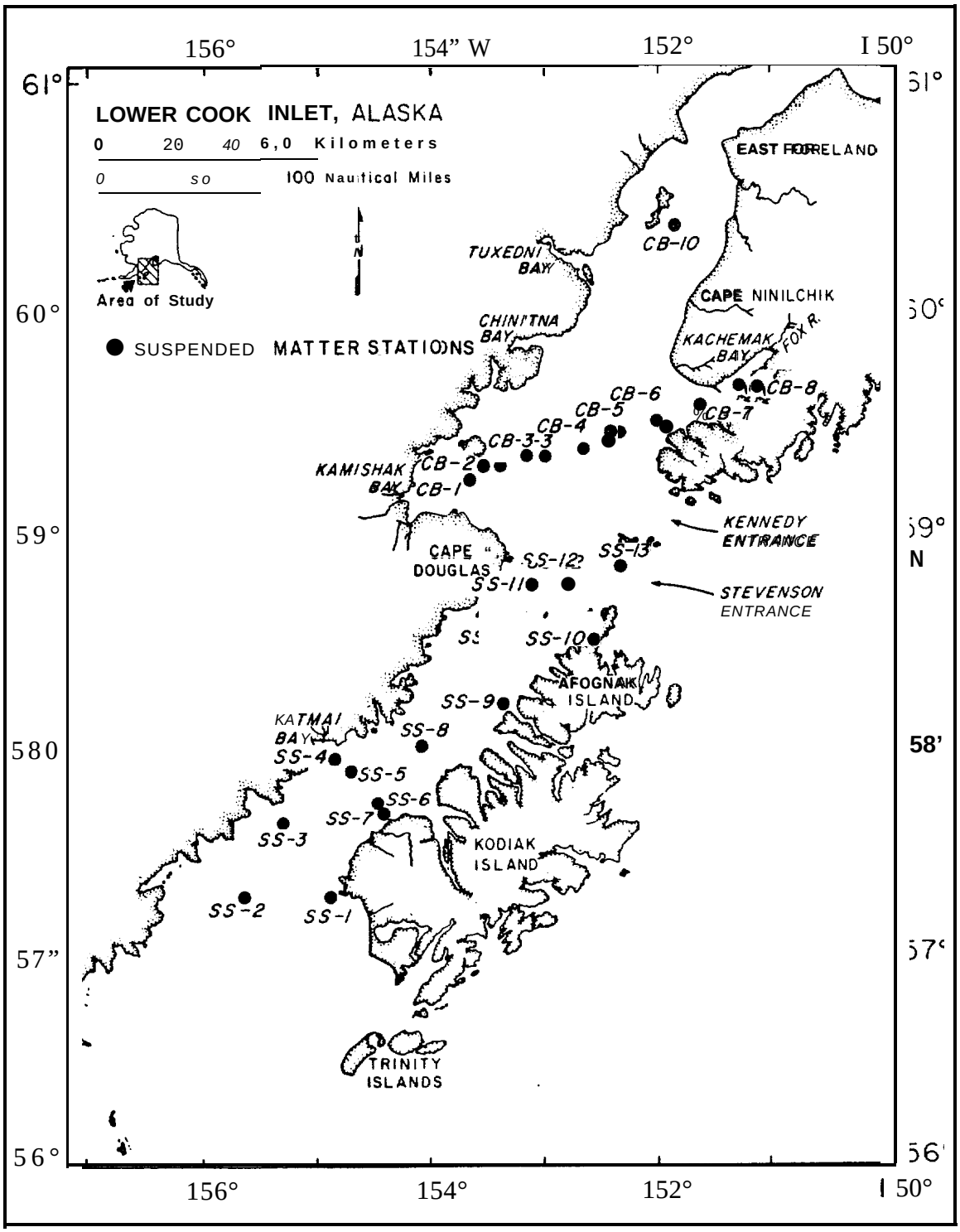

Figure 6. Locations of suspended matter stations in lower Cook Inlet and Shelikof Strait (Cruise RP-4-Di-78B-II, 22 August - 6 September 1978).

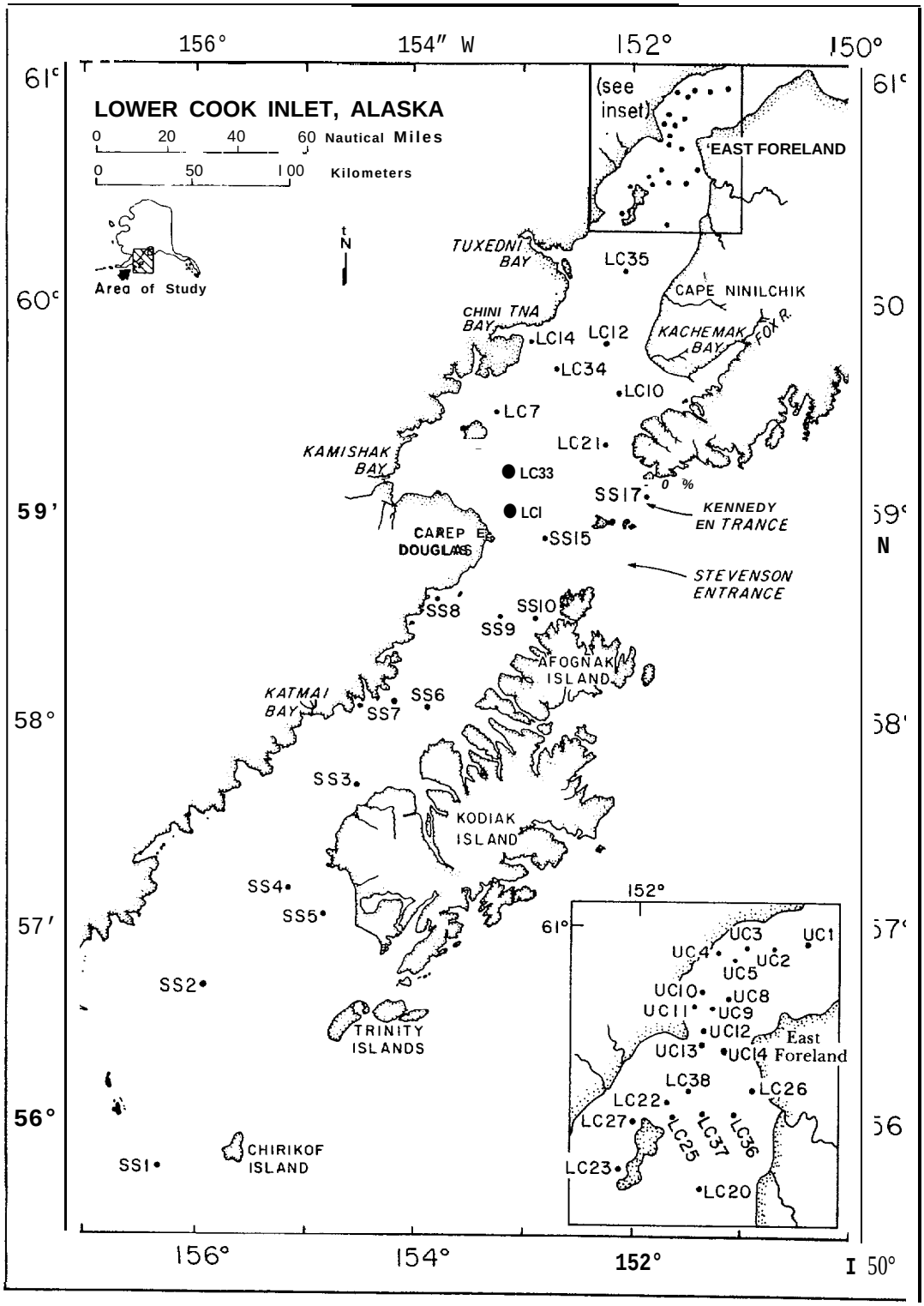

Figure 7. Locations of suspended matter stations in lower Cook Inlet and Shelikof Strait (Cruise RP-4-Di-79A-II, 7 - 20 May 1979).

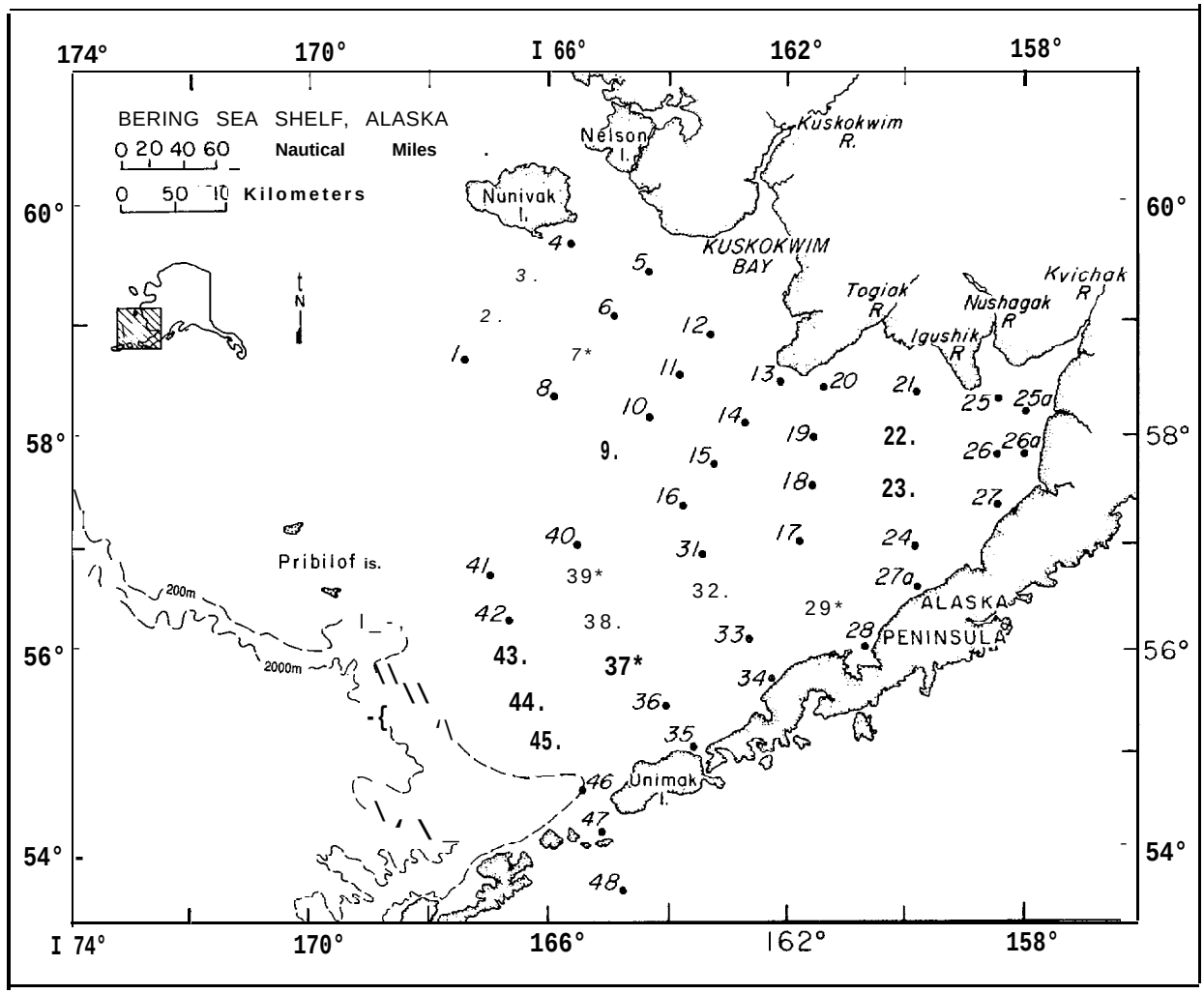

Figure 8. Locations of suspended matter stations in the southeastern Bering Shelf (Cruises RP-4-Di-75B-III, 12 September - 5 October 1975, and RP-4-MW-76B-VIII, 24 June - 9 July 1976).

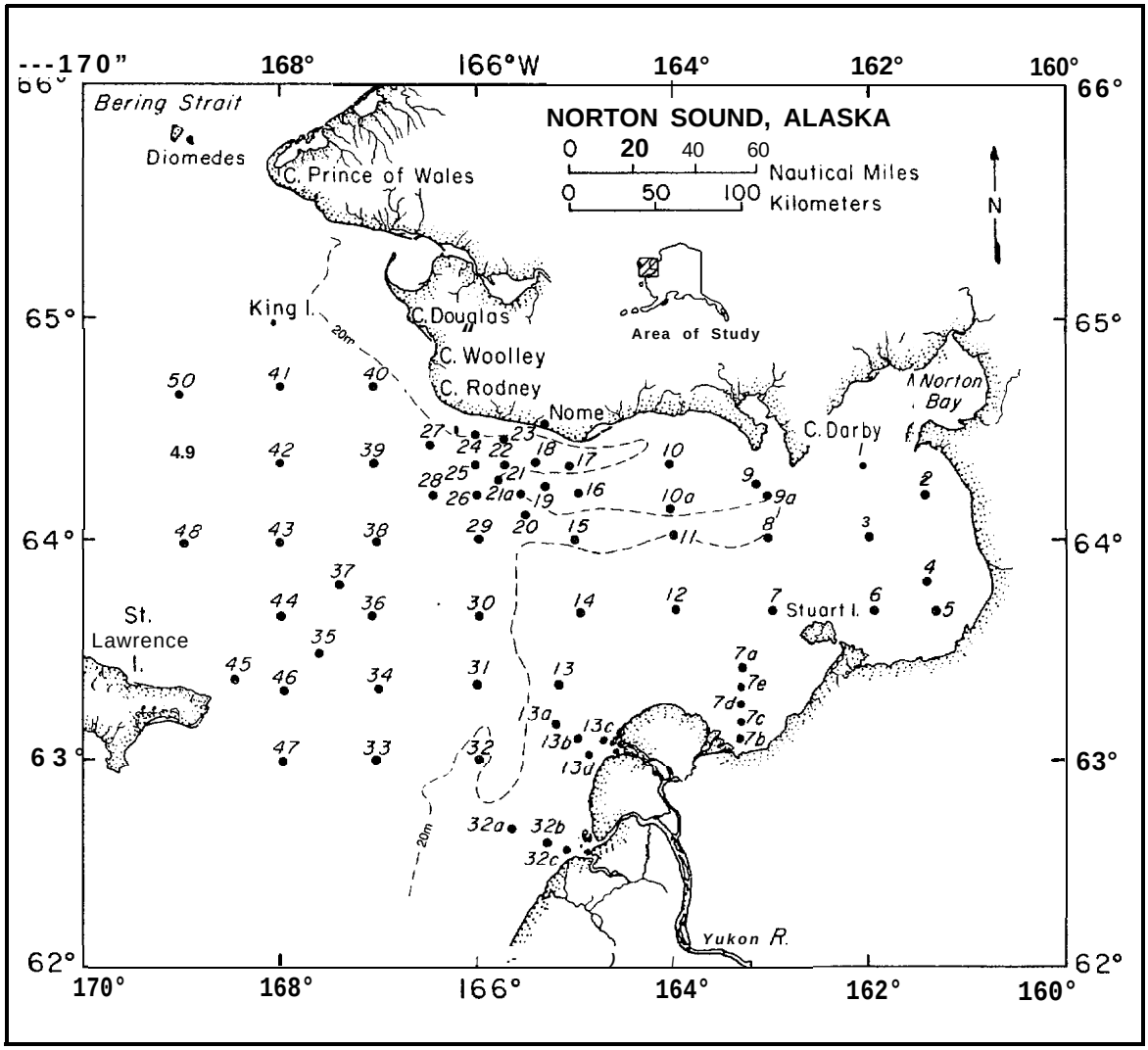

Figure 9. Locations of suspended matter stations in Norton Sound (Cruise RP-4-Di-79A-VI, 7-18 July 1979).

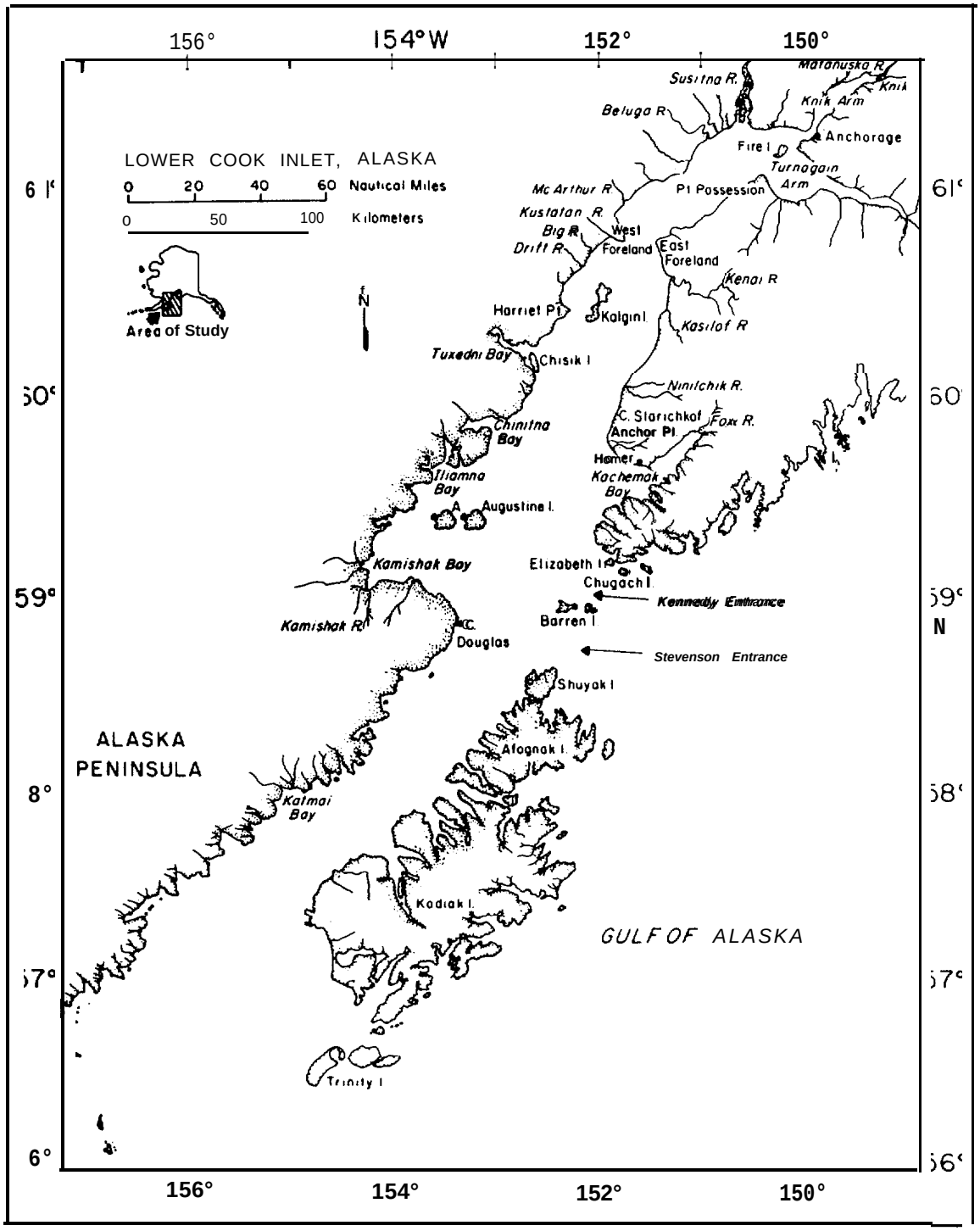

Figure 10. Physiographic setting of lower Cook Inlet, Alaska.

5.1.3 Conductivity (Salinity), Temperature, and Depth

These standard hydrographic data were acquired with a Plessy Model 9040 Environmental Profiling System (CTD probe) and a Model 8400 digital data logger using 7-track, 200 B.P.I. magnetic tape. Temperature and salinity calibration data were provided by ship personnel from discrete water samples utilizing reversing thermometers and a bench salinometer, respectively. Signals from the CTD system and the nephelometer were also simultaneously interfaced with the ship's data acquisition system. This resulted in computer listings of continuous (uncorrected) data for conductivity, temperature, depth, salinity, sigma-t, and light scattering for all vertical. sampling stations.

5.2 Analytical Methods

5.2.1 Gravimetry

Total suspended matter concentrations were determined gravimetrically. Volumetric total suspended matter samples were collected on 47 mm, 0.4 μm pore diameter Nuclepore filters which were weighed on a Cahn Model 4700 Electrobalance before and after filtration. The suspended matter loadings were then determined by difference. The weighing precision ($2\sigma = \pm .011$ mg) and volume reading error (± 10 mL) yield a combined coefficient of variation in suspended matter concentration (mg/L) at mean sample loading and volume (2.057 mg and 2 L, respectively) of approximately 1%. However, preliminary investigations of sampling precision (coef. of var.: 25%) suggest that the actual variability in the particulate matter concentrations of these waters is much greater than the above analytical precision.

5.2.2 Gas Chromatography

Analysis of total particulate C and N in suspended matter was performed with a Hewlett Packard Model 185B C-H-N analyzer. In this procedure, particulate C and N compounds are combusted to CO_2 and N_2 (micro Pregl-Dumas method), chromatographed on Poropak Q, and detected sequentially with a thermal conductivity detector. NBS acetanilide is used for standardization. Analyses of replicate surface samples yield coefficients of variation ranging from 2% to 10% for C and 7% to 14% for N.

5.2.3 X-ray Secondary Emission Spectrometry

The major (Mg, Al, Si, K, Ca, Ti, and Fe) and trace (Cr, Mn, Ni, Cu, Zn, and Pb) element chemistry of the suspended particulate matter samples was determined by x-ray secondary emission (fluorescence) spectrometry utilizing a Kevex Model 0810A-5100 x-ray energy spectrometer and the thin-film technique (Baker and Piper, 1976). The inherent broad band of radiation from a Ag x-ray tube was used to obtain a series of characteristic emission lines from a single element secondary target which then more efficiently excited the thin-film sample. Fe, Se and Zr secondary targets were used to analyze the samples for both major and trace elements. Standards were prepared by passing suspensions of finely ground USGS standard rocks (W1, G-2, GSP-1, AGV-1, BCR-1, PCC-1) and NBS trace element standards through a 37 μm mesh polyethylene screen followed by collection of the size fractionated suspensates on Nuclepore filters identical to those used for sample acquisition. The coefficient of variation for 10 replicate analyses of a largely inorganic sample of approximately mean mass was less than 3% for the major constituents and as high as 5% for the trace elements. However, when sampling precision is considered, the coefficients of variation increase, averaging 12% and 24% for major and trace elements, respectively.

5.2.4 Atomic Absorption Spectrophotometry

The suspended matter samples from lower Cook Inlet and Norton Sound were analyzed for Al, Fe, Mn, Cr, Cu, Ni, Zn and Pb by means of several extraction procedures. The first extraction procedure involves the use of hydrogen peroxide (H_2O_2) to release organically-bound trace metals. The second treatment utilizes 0.3 N hydrochloric acid (HCl) to release trace metals which are weakly bound to inorganic phases. The third procedure involves the use of 25% acetic acid (CH_3COOH) to remove amorphous Fe and Mn oxides. The details and validity of these procedures are outlined below.

5.2.4.1 H_2O_2 Treatment

Crecelius et al. (1974) have demonstrated that 30% H_2O_2 efficiently oxidizes particulate organic matter and thus removes certain trace metals from sediments. Landing (1978) had shown that the modification of this procedure, as described below, efficiently removes organic C and N from suspended matter. The release of trace metals from suspended matter during this procedure is attributed to the dissolution of organically bound trace metals.

Procedure. Dilute 30% ULTREX (J.T. Baker) H_2O_2 to 10% with the addition of quartz distilled water (Q-H_2O). Combine 5 mLs of 10% H_2O_2 with 100-500 mg of sample material in a precleaned centrifuge tube equipped with a nonsealing cap. The volume and mass of extractant and sample, respectively, may vary within the above limits depending on the relative magnitude of the organic fraction in the sample. We are currently using polypropylene centifuge tubes and caps. Heat the extractant-sediment solution in a water bath at approximately 50°C for 48 hours. During the final 24 hours of heating, vigorously sonicate the solution to assist in dispersal and breakdown of the organic matter. Centrifuge the tube contents at 2000 rpm for 1 hour. Decant the supernate into a precleaned and tared polyethylene (CPE) bottle. Rinse the residual particulate matter with one 10 mL aliquot of quartz-distilled water. Centrifuge, as above, after the rinse and combine all supernates in the polyethylene bottle. Since the centrifugation separation is not complete, filter the samples through a 0.4 μm Nuclepore filter. Determine the weight of the supernate by difference.

5.2.4.2 0.3 N HC1 Treatment

Malo (1977) has shown that leaching with hot 0.3 N HC1 is the most effective method for dissolving trace metals associated with surface coatings. In this study, this method was modified by heating the sediment-0.3 N HCl mixture to 75°C instead of 100°C. The time required for completion of the reaction was determined by leaching subsamples for different lengths of time. The results of this kinetic study (fig. 11) indicate that no additional Cu is released after the first 2 hours while Ni and Zn continue to be leached for 12 hours. Therefore, the sediment-acid mixture was heated for 24 hours to insure that the reaction was complete. A high efficiency for this reaction was confirmed by analyzing the amount of Cu and Mn released on a subsequent 0.3 N HCl leach (table 1).

Procedure. Dilute ULTREX (J.T. Baker) HC1 to 0.3N with Q-H_2O. Add 8 mLs of 0.3 N HCl to 100-500 mg of sample which has been treated with H_2O_2. Heat the mixture to 75°C for 24 hours while sonicating. Centrifuge the mixture at 2000 rpm for 1 hour. Decant the supernate into a precleaned and tared polyethylene bottle. Add 8 mLs of 0.3 N HCl to the residual sediment. Shake this mixture, then centrifuge as above and decant the supernate into the bottle. Repeat the rinsing of the residual sediment once. Filter the combined supernates through a 0.4 µm Nuclepore filter. Determine the weight of the final supernate by difference.

Table 1. Efficiency of Successive 0.3 N HC1 Treatments

	Mn (ppm)	Cu (ppm)
First Treatment (n = 3)	911 ± 78	49.3 ± 2.5
Second Treatment (n = 3)	6.7 ± 0.3	0.7 ± 0.1

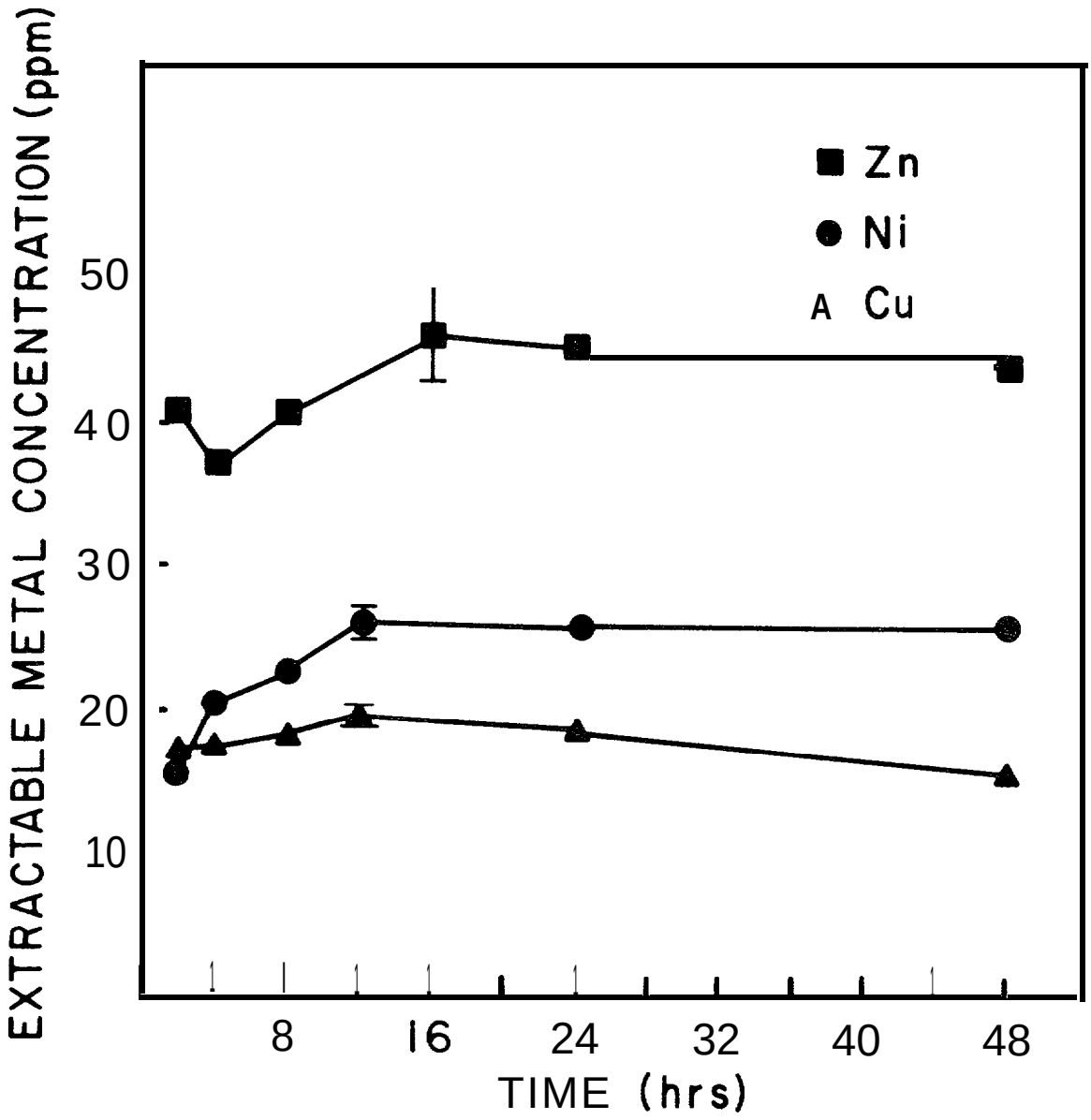

Figure 11. Extractable metal concentrations versus time in contact with 0.3 N HC1 for Zn, Ni, and Cu. The range of values is given for duplicate samples at 12 hours.

5.2.4.3 25% Acetic Acid

The amorphous Mn and Zn in the poorly structured oxyhydroxide phase of selected suspended matter samples were determined by the method of Bolger et al. (1978). Desiccated samples were leached with 5 mL of 25% (v/v) Ultrex acetic acid at room temperature for 2 hours. The resulting supernate was filtered through an acid-cleaned polypropylene-glass apparatus containing a 0.4 μm Nuclepore filter. The residue was rinsed with quartz-distilled water, then filtered; and the supernate was combined with the original supernate, acidified with 0.5 mL of concentrated Ultrex HCl, and stored in an acid cleaned polyethylene bottle. The Mn and Zn in this solution (weak-acid soluble) were analyzed by flameless atomic absorption procedures using addition methods. The remaining solid suspended matter (weak-acid insoluble) was dissolved in an Ultrex HCl - HNO_3 - HF matrix according to Eggiman and Betzer (1976) and analyzed for Mn and Zn in a similar manner.

5.2.4.4 Bulk Elemental Analysis

Elemental composition of suspended matter was determined using a modification of the method of Eggiman and Betzer (1976).

> Procedure. If the sediment is refractory, grind the dry sediment in a boron carbide mortar and pestle. Weigh out approximately 2 mg and place in a digestion bomb (Bombco, Inc.). Add 0.75 mL of 12 NHC1 (ULTREX) and seal the bomb tightly and place in boiling water for 45 minutes. Cool for 45 minutes in a freezer. Add 0.25 mL of 16 N HNO_3 (ULTREX), seal, and place in boiling water for 45 minutes. Cool for 45 minutes in freezer. Add .05 mL of concentrated HF (ULTREX), seal, and place in boiling water for 90 minutes. Cool for 90 minutes. Quantitatively transfer the contents of the digestion bomb to a wide mouth bottle and rinse the bomb with Q-HzO. Dilute the sample to 20 gm with Q-HzO.

5.2.4.5 Instrumental Procedures

Flameless atomic absorption measurements were made using a Perkin-Elmer 603 spectrophotometer equipped with an HGA-2200 furnace control, deuterium arc background corrector, AS-1 automatic sampler and a Model 54 recorder. The normal instrument parameters are listed in table 2. Baker AAS standards are diluted in a matrix similar to the samples. The instrument was calibrated using this standard which covered the absorbance range of the samples. The total dissolution analysis for Al was done by the standard addition method.

Table 2. Summary of the analytical parameters utilized in the flameless atomic absorption determinations. Analyses conducted with a Perkin-Elmer 603 AAS, D-2 Arc Background Corrector, HGA-2200 Flameless Atomizer, AS-1 Automatic Sampler. Pyrolitically coated tubes used for all elements. Std. Add. = Standard Additions.

Element	Wavelength (m)	Slit (nm)	Volume (µl)	Dry Cycle (Time/Temp	Ash Cycle Time/Temp	Atomize Cycle Time/Temp	Gas	Flow Units	Bkg. Cor.	Comments
Al	257	0.2	10	30/100	22/1300	5/2600	Ar	40	No	Std. Add.
Fe	347	0.2	10	30/100	22/1050	5/2600	‘2	40	No	
Mn	280	0.2	10	30/100	22/1000	5/2600	‘2	55	No	
Cr	358	0.7	10	30/100	22/1000	5/2600	Ar	45	No	
Cu	325	0.7	10	30/100	22/ 800	5/2500	Ar	35	No	
Ni	232	0.2	20	40/100	32/ 900	5/2500	Ar	35	Yes	
Pb	217	0.7	20	40/100	32/ 600	5/2500	Ar	35	Yes	
Zn	214	0.7	10	30/100	22/ 500	5/2500	Ar	40	Yes	

6. RESULTS AND DISCUSSIONS

6.1 Northeast Gulf of Alaska

6.1.1 Particulate Matter Distributions and Transport

Figures 12 thru 17 show the distributions of suspended matter at the surface and 5 m above the bottom for the fall, spring, and summer cruises, respectively. The surface distributions showed significant variations which can be related to fluctuations in sediment flux from coastal rivers, formation of eddies, and local variations in current patterns and transport processes; whereas near-bottom distributions appeared to be affected primarily by local variations in bottom currents and secondarily by regional sources.

East of Kayak Island, surface particulate matter distributions were dominated by the discharge of sedimentary material from the coastal streams which drain the Bering, Guyot, and Malaspina glaciers. As this material was discharged into the Gulf, coastal along-shelf currents quickly advected it to the west along the coast. Comprehensive analyses of LANDSAT imagery for this region (Sharma et al., 1974 and Carlson et al., 1975) have indicated that most of the material discharged from the rivers east of Kayak Island remains relatively close to the coast (within 40 km) until it reaches Kayak Island, where it is deflected offshore. Surface particulate matter distributions for the cruises in October and April (figs. 12 and 13) followed this pattern. Along the transect southeast of Icy Bay (stations 10-13), particulate matter concentrations in fall and spring decreased from >1.0 mg/L near the coast to >0.5 mg/L approximately 40 km off the coast. During July, however, a plume of turbid water was observed extending outward from the coast (fig. 14). From careful analysis of LANDSAT imagery for this area, Burbank (1974) observed that occasionally counterclockwise eddies were formed which transported plumes of terrigenous material offshore. Similar low frequency motions were observed

in current meter records from stations located southwest of Icy Bay (Hayes and Schumacher, 1976).

During fall and spring, plumes of turbid water (>1.0 mg/L) extended to the southwest from Kayak Island. From an analysis of LANDSAT-1 satellite photographs taken on August 14, 1973, Sharma et al., (1974) postulated that terrigenous debris discharged from the coastal rivers east of Kayak Island is carried to the west around the island's southern tip (Cape St. Elias)" and trapped by a quasi-permanent anticyclonic gyre. Our data from the October and April cruises support their hypothesis (figs. 12 and 13). During October, a turbid plume extended to the west about 100 km from Kayak Island to station 33 (fig. 12). Particulate concentrations within the plume were high, averaging about 1.5 mg/L. North and south of station 33, particulate concentrations dropped below 1.0 mg/L, suggesting that the plume had an eastern origin. In April, a similar plume extended 50 km southwest of Kayak Island (fig. 13), with particulate concentrations decreasing from east to west. These similarities in the suspended matter distribution patterns suggest that, at the time of the cruises, similar hydrographic processes were operating to cause offshore transport of suspended matter.

In July, particulate distributions were significantly different from the preceding cruises. Near Kayak Island, there was no evidence of plumes extending offshore (fig. 14). A zone of turbid water extended only about 4 km from the eastern coast of Kayak Island, around the southern tip of the island and northward along the western coast. Near the mouth of the Copper River a plume of highly turbid water extended as far as 40 km offshore. Suspended matter concentrations within the plume were the highest of the three cruises, averaging 6.7 mg/L, reflecting the increased sediment discharge during July. As with the previous two cruises, sedimentary material from the Copper River

was carried west along the coast until it reached Hinchinbrook Island. A portion of the material passed into Prince William Sound from either side of the island and the remaining material was carried southwest along the southern coast of Montague Island.

The distribution of suspended matter 5 m above the bottom for the three cruises is shown in figures 15, 16, and 17. The concentration data must be considered with some caution because the sampling was conducted with respect to the bottom and actual depths vary with the topography. Nevertheless, the data show a consistent pattern of decreasing concentrations away from the coast. Near-bottom concentrations were highest in the region south of the Copper River Delta and on either side of Kayak Island, where particulate concentrations ranged between 1.1 and 10.4 mg/L. At the edge of the continental shelf, near-bottom distributional patterns have been described previously for the continental shelf of the United States (Meade et al., 1975; Biscaye and Olsen, 1976) and have been attributed to resuspension of fine-grained sediments. The near-bottom turbid plumes in the northeast Gulf were primarily located over regions dominated by modern accumulations of clayey silts and silty clays (Carlson et al., 1977) and showed little resemblance to the surface plumes in space and time. These data suggest that bottom sediments were being resuspended locally to form near-bottom nepheloid layers in the Gulf, either by the actions of bottom currents, waves, or benthic organisms.

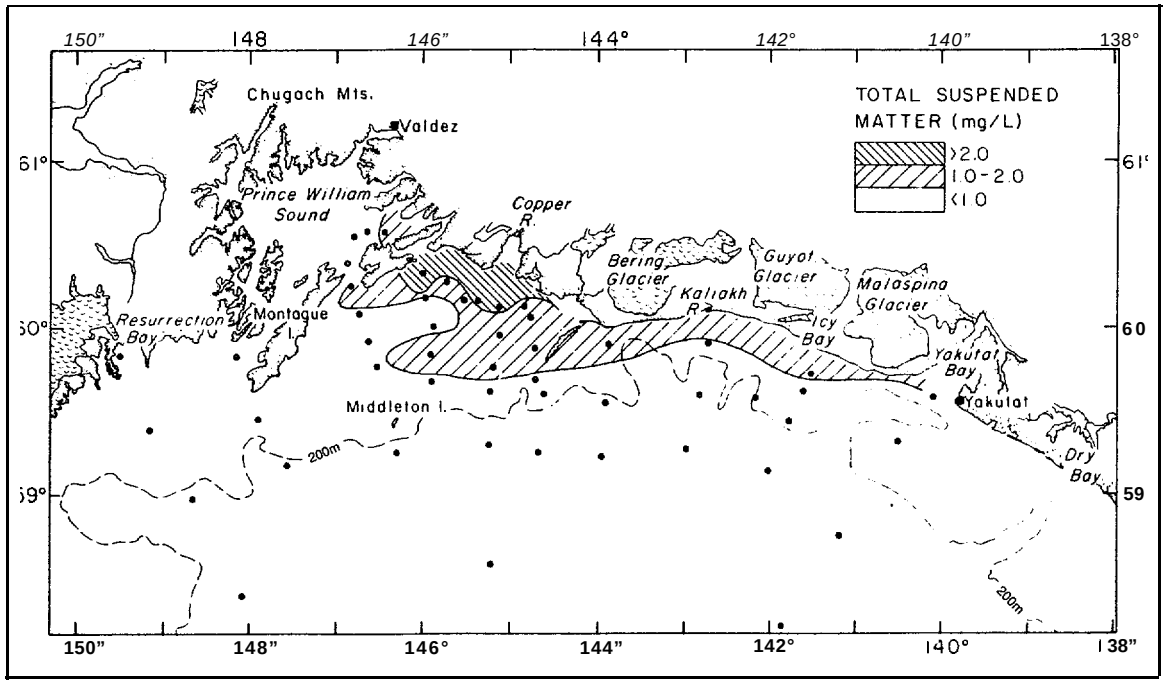

Figure 12. Distribution of total suspended matter at the surface in the northeastern Gulf of Alaska (Cruise RP-4-Di-75C-I, 21 October - 10 November 1975).

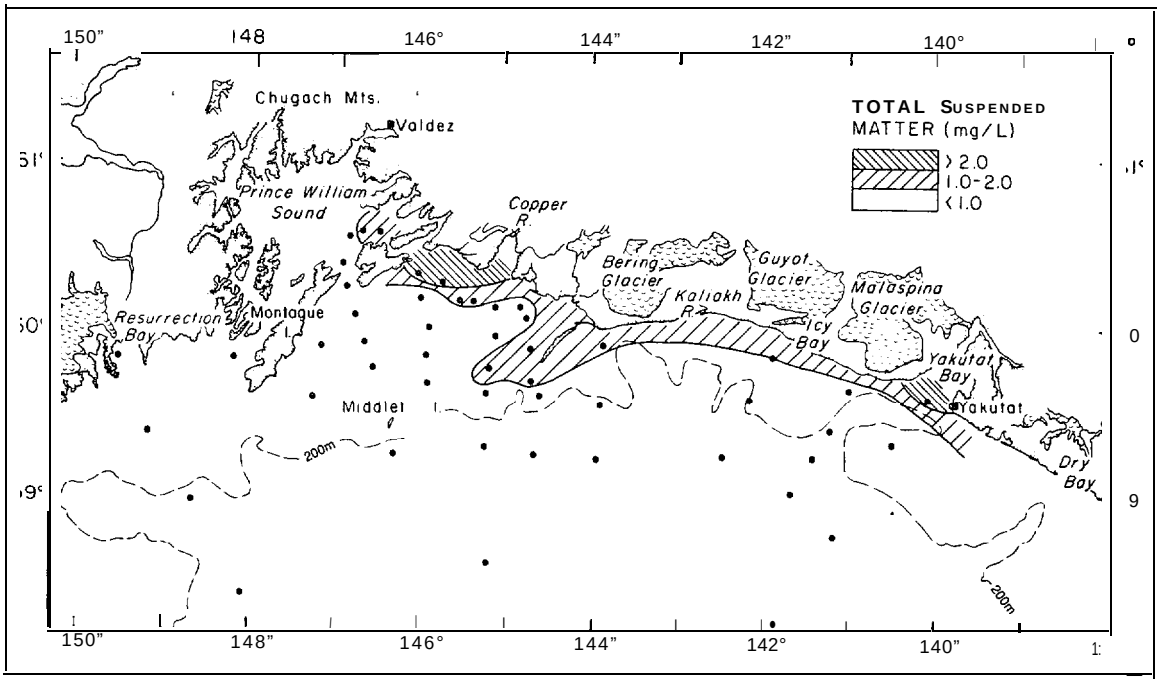

Figure 13. Distribution of total suspended matter at the surface in the northeastern Gulf of Alaska (Cruise RP-4-DI-76A-III, 13-30 April 1976).

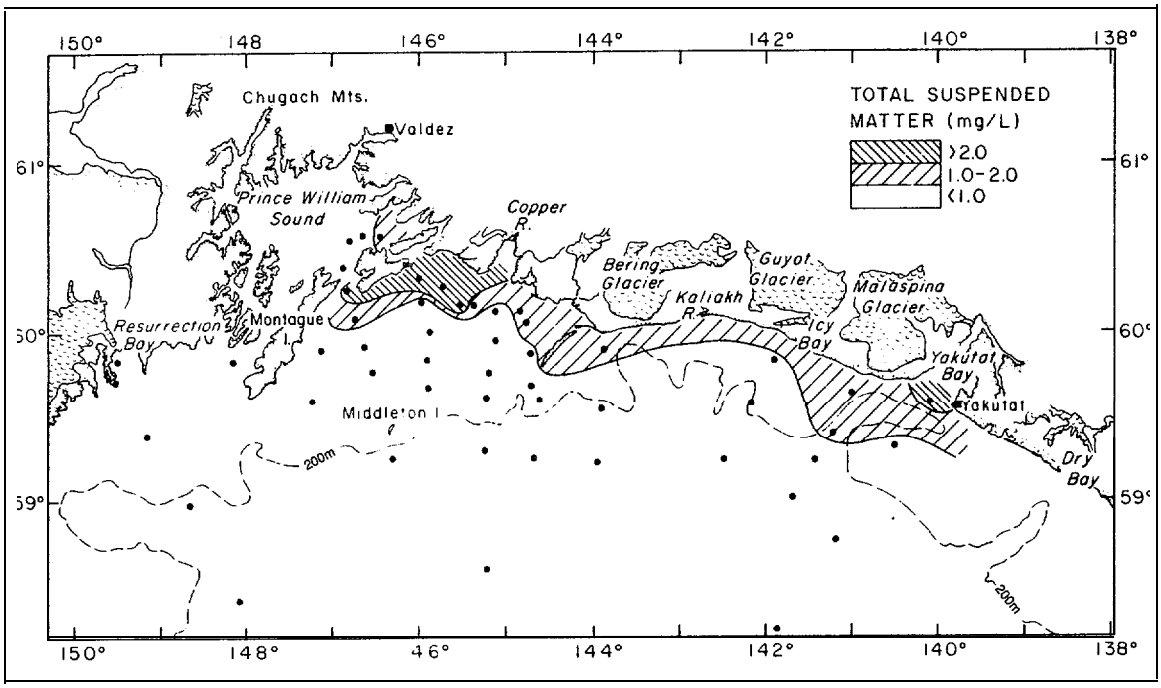

Figure 14. Distribution of total suspended matter at the surface in the northeastern Gulf of Alaska (Cruise RP-4-Di-76B-I, 19-31 July 1976).

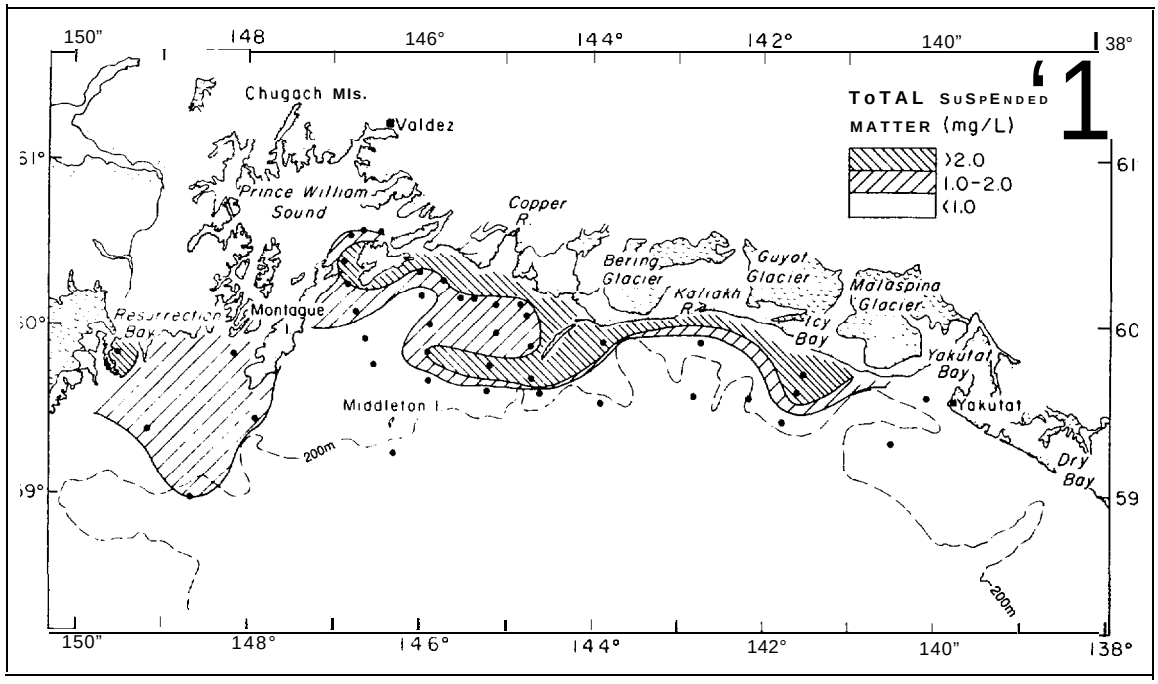

Figure 15. Distribution of total suspended matter at 5 meters above the bottom in the northeastern Gulf of Alaska (Cruise RP-4-Di-76B-I, 21 October - 10 November 1975).

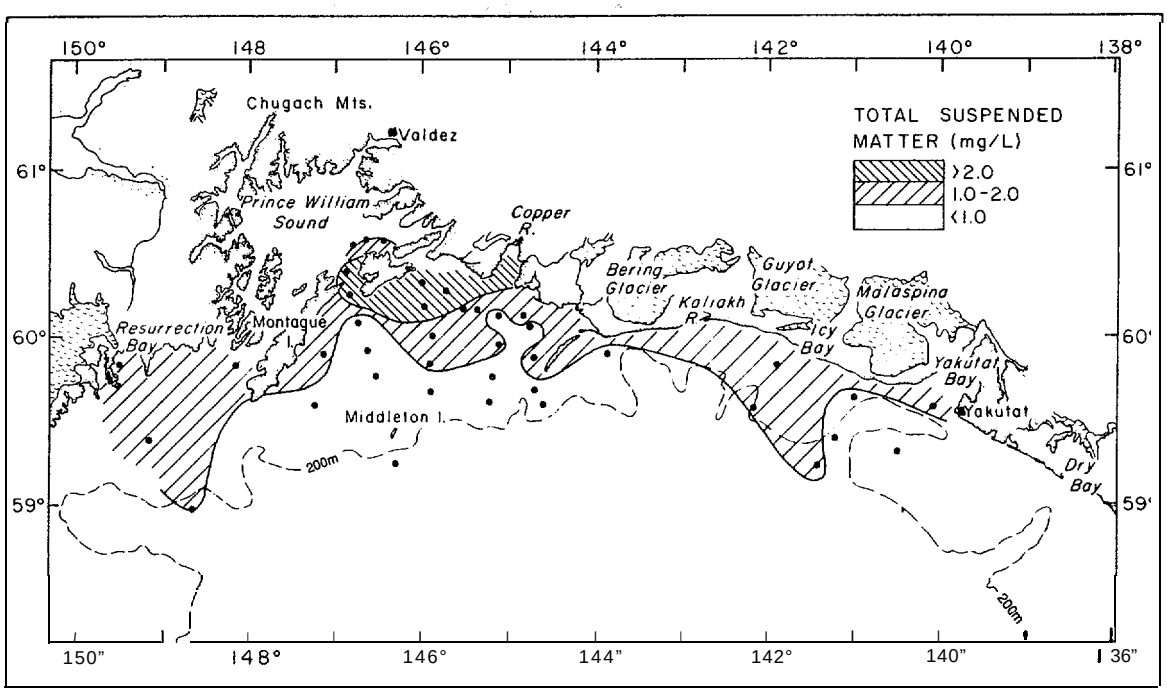

Figure 16. Distribution of total suspended matter at 5 meters above the bottom in the northeastern Gulf of Alaska (Cruise RP-4-Di-76A-III, 13-30 April 1976).

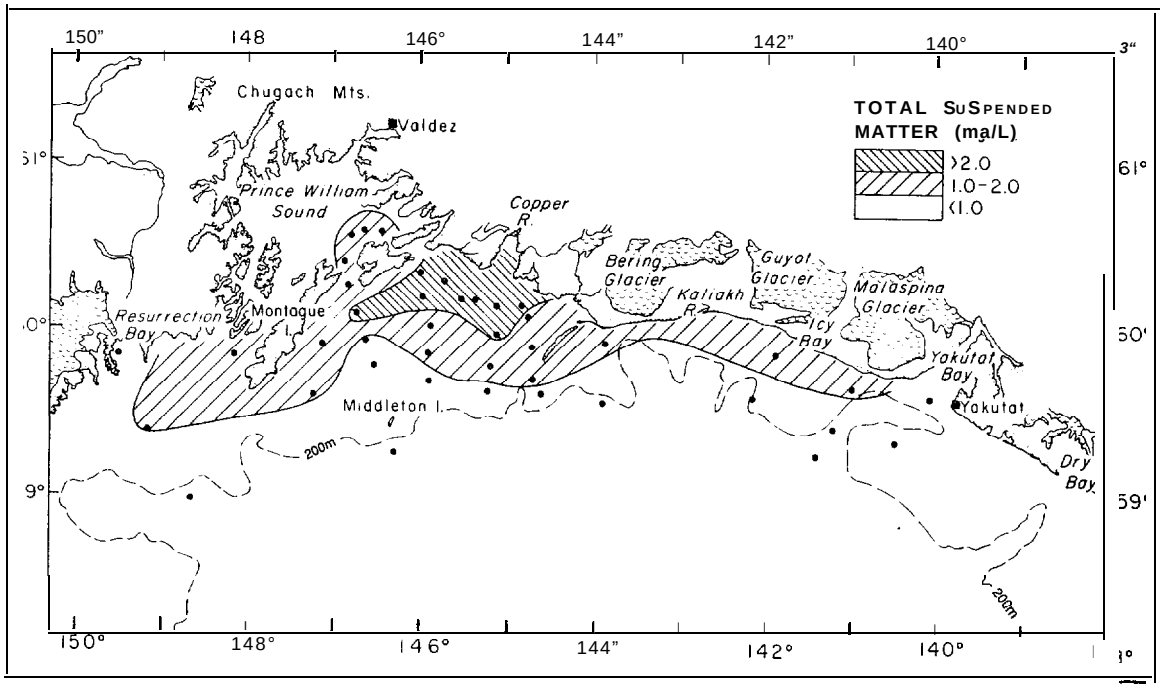

Figure 17. **Distribution of total suspended matter at 5 meters above the bottom in the northeastern Gulf of Alaska (Cruise RP-4-Di-76B-I, 19-31 July 1976).**

6.1.2 Elemental Composition of the Suspended Matter

Table 3 compares summaries of the data on the elemental composition of suspended matter from the Copper River with summaries of the surface and near-bottom suspended matter from the Gulf of Alaska. The data for the underlying sediments are given in table 4 and average element/Al ratios for the three cruises are given in table 5. The data for the Gulf surface suspended matter samples have been arranged into three groups. Group I contains all samples in which the sum of the major inorganic element concentrations (expressed as oxides) is greater than 75% of the total suspended load; samples containing inorganic sums ranging between 31% and 75% comprise Group II, and samples containing less than 31% inorganic sum are in Group III. In general, Group I samples are primarily composed of clay-sized terrestrial particles from the coastal rivers and are located in the nearshore stations and offshore from Kayak Island. Group II samples are composed of mixtures of terrestrial and biogenic matter and are located near the shelf break; and Group III samples are primarily composed of biogenic particles of marine origin and are found seaward of the shelf break.

The elemental compositions and element/Al ratios illustrate some compositional differences between near-shore (Group I) and offshore (Group 111) suspended matter. Since most of the Al in marine particulate matter is located in aluminosilicate material (Sackett and Arrhenius, 1962) and because marine plankton contains only about 500 ppm Al by weight (Martin and Knauer, 1973), the Al concentrations in the suspended matter can be used to estimate aluminosilicate percentages in the particulate matter (Al x 10). Similarly, Gordon (1970) suggested that particulate C may also be used to estimate the amount of organic matter in the suspended matter by multiplying the particulate C content by a factor 1.8. Based on the particulate Al and particu-

TABLE 3

Summary of the elemental composition of particulate matter collected from the Copper River and the northeast Gulf of Alaska. The Copper River particulate matter was collected during high discharge conditions (June 1976) from a position 10 km landward of the river mouth. The 1σ precision values are from replicate analyses of a near surface sample. For the northeast Gulf of Alaska data groups, the 1σ averaging precision is given. Superscripts indicate the number of elemental values averaged when different from the number of samples in the respective group.

Sample Location	No. of samples	C wt. %	N wt. %	Al wt. %	Si wt. %	K wt. %	Ca wt. %	Ti wt. %	Cr ppm	Mn ppm	Fe wt. %	Ni ppm	Cu ppm	Zn ppm
Copper River	1	1.0 ± .5	.1 ± .1	9.3 ± .2	27.9 ± .5	1.8 ± .1	4.4 ± .1	.64 ± .01	126 ±13	1210 ± 50	6.7 ± .2	61 ± 5	63 ± 2	133 ± 5
October-November 1975														
Surface (Group I)	11	11.4[9] ±4.7	1.6[9] ± .8	10.2 ±1.3	29.7 ±2.1	1.5 ± .2	3.3 ±1.3	.57 ± .06	119 ±18	1200 ±120	6.5 ± .8	81 ±19	109 ±20	210 ±58
Surface (Group II)	6	33.8[5] ±5.9	4.7[5] ±1.2	4.1 ±1.7	18.0 ±5.6	0.6 ± .2	2.1 ± .9	.27 ± .07	75 ±30	660 ±140	3.1 ± .7	62 ±23	195 ±67	270 ±60
Surface (Group III)	2	48.8 ±8.1	6.2 ±1.6	1.5 ± .7	13.9 ±1.0	0.4 ± .3	2.4 ±1.1	.16 ± .13	47 ± 6	410 ±113	2.0 ± .7	58 ±20	116 ± 4	172
5 m above	12	11.3[10] ±5.8	1.4[10] ± .7	9.4 ±1.7	30.7 ±3.6	1.3 ± .3	2.3 ± .7	.50 ± .10	104 ±16	1170 ±210	6.1 ±1.2	79 ±22	100 ±18	184 ±30
April 1976														
Surface (Group 1)	11	6.9 ±3.3	1.2[10] ± .7	10.3 ±1.3	30.8 ±2.2	1.5 ± .2	2.5 ± .8	.54 ± .08	113 ±20	1180 ± 80	6.3 ± .9	78 ±14	55[10] ±11	292 ±154
Surface (Group 11)	6	18.3[5] ±6.9	3.4[5] ±1.0	4.8 ±1.9	19.0 ±7.2	0.6 ± .3	1.1 ± .3	.28 ± .09	67 ±14	740 ±180	3.1 ± .9	46 ±11	26 ±10	307 ±154

TABLE 3 (Continued)

Sample Location	No. of samples	C wt. %	N wt. %	Al wt. %	Si wt. %	K wt. %	Ca wt. %	Ti wt. %	Cr ppm	Mn ppm	Fe wt. %	Ni ppm	Cu ppm	Zn ppm
Surface (Group III)	6	23.7 ±2.1	4.3[5] ± .4	0.5[4] ± .3	19.0 ±14.0	0.1 ± .1	0.5 ± .3	.80 ± .06	35[4] ±14	260 ±210	1.3 ± .8	39[3] ± 7	30[3] ±4	237 ± 67
5 m above the bottom	11	4.8[10] ±1.7	0.8[10] ± .4	10.2 ± .6	30.6 ±1.5	1.5 ± .1	2.9 ± .5	.58 ± .04	116 ± 8	1160 ± 70	6.6 ± .3	79 ±16	56[10] ± 9	194 ± 36
July 1976														
Surface (Group I)	3	5.5 ±2.2	1.0 ± .5	10.3 ±1.0	31.3 ±1.0	1.7 ± .2	3.1 ± .7	.59 ± .10	103 ±18	1260 ± 81	6.5 ±1.0	65 ± 9	97 ± 6	248 ±51
Surface (Group II)	7	21.4 ±6.8	3.8[6] ±1.8	5.5 ±1.3	28.4 ±7.1	0.9 ± .2	1.3 ± .3	.28 ± .05	78 ±24	930 ±160	3.7 ± .5	55 ±12	125 ±38	264 ±152
Surface (Group III)	10	28.5 ±7.7	4.6[9] ±2.0	1.1[9] ± .7	15.8 ±6.7	0.4[9] ± ,5	0.4 ± .2	.10 ± .03	68[7] ±45	340 ±200	1.4 ± .6	57[3] ±20	87 ±23	232 ±112
5 m above the bottom	15	4.8 ±3.6	0.7[14] ± .6	10.8 ± .7	31.3 ±1.6	"1.6 ± .2	2.8 ± .6	.58 ± .05	119 ±15	1330 ±180	6.8 ± .6	67 ±15	95 ±18	214 ±56

TABLE 4

Summary of the elemental composition of sediment samples from the northeast Gulf of Alaska*

Sample Description	No of Samples	Al wt. %	Ca wt. %	Fe wt. %	Mn ppm	Cr ppm	Ba ppm
	15	7.24 ±0.85	4.10 ±2.20	4.64 ±0.88	813 ±111	126 ±22	503 ±118

*Data from Robertson and Abel as reported in Burrell (1977).

TABLE 5

Summary of elemental ratios to aluminum for particulate matter samples from the Copper River and the Northeast Gulf of Alaska. The 1σ precision values were determined by propagation of errors from data given in table 3.

Sample Description	C/Al	N/Al	Si/Al	K/Al	Ca/Al	Ti/Al	Cr/Al $X10^{-3}$	Mn/Al $X10^{-3}$	Fe/Al	Ni/Al $x10^{-3}$	Cu/Al $X10^{-3}$	Zn/Al $x10^{-3}$
Copper River	.11 ±.05	.01 ±.01	3.0 ±.1	.19 ±.01	.48 ±.01	.07 ±.01	1.3 ±.1	13 ±1	.72 ±.03	.66 ±.02	.68 ±.03	1.4 ± -
October-November 1975												
Surface (Group I)	1.1 ±.5	.16 ±.08	2.9 ±.4	.15 ±.03	.32 ±.13	.06 ±.01	1.2 ±.2	12 ±2	.64 ±.11	.79 ±.21	1.1 ±.2	2.1 ±.6
Surface (Group II)	8.7 ±3.7	1.2 ±.6	4.4 ±2.3	.15 ±.08	.51 ±.31	.07 ±.03	1.8 ±1.1	16 ±8	.76 ±.36	1.5 ±.8	4.8 ±2.6	6.6 ±3.1
Surface (Group III)	33 ±16	4.1 ±2.2	9.3 ±4.4	.23 ±.23	1.6 ±1.1	.11 ±.10	3.1 ±1.5	27 ±15	1.3 ±.8	3.9 ±2.2	7.7 ±3.6	11 ± -
5 m above the bottom	1.2 ±.7	.15 ±.08	3.3 ±.7	.14 ±.04	.24 ±.09	.05 ±.01	1.1 ±.3	13 ±3	.65 ±.17	.84 ±.28	1.1 ±.3	2.0 ±.5
April 1976												
Surface (Group I)	.67 *.33	.12 ±.07	3.0 ±.4	.15 ±.03	.24 ±.08	.05 ±.01	1.1 ±.2	12 ±2	.61 ±.12	.76 ±.17	.53 ±.13	2.8 ±1.5
Surface (Group II)	3.8 ±2.1	.71 *.35	4.0 ±2.2	.13 ±.07	.23 ±.11	.06 ±.03	1.4 ±.6	15 ±7	.65 ±.32	.96 ±.44	.65 ±.44	6.4 ±4.1
Surface (Group III)	47 ±29	8.6 ±5.2	38 ±36	.22 ±.21	1.00 ±.81	.16 ±.15	7.0 ±5.1	52 ± 52	2.6 ±2.2	7.8 ±4.8	6.0 ±3.7	47 ±31

TABLE 5 (Continued)

Sample Description	C/Al	N/Al	Si/Al	K/Al	Ca /Al	Ti/Al	Cr/Al Xlo^{-3}	Mn/Al Xlo^{-3}	Fe/Al	Ni/Al Xlo^{-3}	Cu/Al Xlo^{-3}	Zn/Al Xlo^{-3}
5 m above the bottom	.47 ±.17	.08 ±.14	3.0 ±.2	.15 ±.01	.28 ±.06	.06 ±.01	1.1 ±.1	11 ±1	.65 ±.05	.77 ±.16	.55 ±.09	1.9 ±.4
July 1976												
Surface (Group I)	.53 ±.22	.10 ±.05	3.0 ±.3	.17 ±.03	-30 ±.07	.06 ±.01	1.0 ±.2	12 ±1	.63 ±.11	.63 ±.11	.94 ±.11	2.4 ± 1.06
Surface (Group II)	3.9 ±1.5	.69 ±.37	5.2 ±1.8	.16 ±.05	.24 ±.08	.05 ±.02	1.4 ±.6	17 ±5	.67 ±.18	1.0 ±.3	2.3 ±.9	4.8 ±3.0
Surface (Group III)	25 ±18	4.2 ±3.2	± 14 11	.34 ±.49	.40 ±.34	.09 ±.06	6.2 ±5.7	31 ±27	1.3 ±1.0	5.2 ±3.8	7.9 ±5.6	21 ±17
5 m above the bottom	.44 ±.33	.06 ±.06	2.9 ±.2	.15 ±.02	.26 ±.06	.05 ±.01	1.1 ±.2	12 ±2	.63 ±.07	.62 ±.14	.88 ±.18	2.0 ±.5

late C concentrations, approximately 103(±13)% and 15 (±6)%, respectively, of the suspended matter from Group I is aluminosilicate material and organic matter. Within the statistical limits of the measurements, nearly all the elemental concentrations of the Group I samples are the same as the river samples, indicating that the coastal rivers are the major source of the inorganic material. Only particulate C and N show significant enrichments over the river suspended matter; this is probably due to production of organic matter in near-shore waters (Larrance et al., 1977).

In contrast to the near-shore samples, the offshore samples (Groups II and III) are significantly depleted in particulate Al, Si, K, Ti, Cr, Mn, Fe, Ni, and Zn; and are enriched in particulate C and N. These depletions are attributed to a drop in the relative amount of aluminosilicate material in the suspended matter (<15% by weight for the Group III samples) and an increase in the proportion of organic matter (>40% by weight) , which is depleted in these elements relative to aluminosilicate material (Martin and Knauer, 1973). Particulate Cu is relatively depleted in the samples taken during the spring cruise and enriched in the samples taken during the summer cruise. This may be due to selective uptake of Cu by some planktonic organisms during a particular phase of their growth cycle, as suggested by the data of Morris (1971) and again by Martin and Knauer (1973).

Table 5 shows the average elemental concentration ratios to Al for the samples from the various groups. The Si/Al and C/Al ratios from Group III are considerably elevated over ratios for the river samples. This is due to the presence of biogenic Si and biogenic C in the suspended matter. Price and Calvert [1973) and Feely (1975) demonstrated that the amount of biogenic Si and biogenic C can be estimated by assuming a constant Si/Al and C/Al ratio due to suspended aluminosilicates and terrestrial C, respectively. Any excess Si and

C is assumed to be of biogenic origin. Using the Si/Al and C/Al of the suspended material from the Copper River, values of approximately 14 (±12)% and 29 (±19)% by weight of the Group III samples are estimated to be composed of biogenic Si and biogenic C, respectively. In contrast, it is estimated that on the average, the Group I samples only contain about 8% by weight biogenic C and < 1% biogenic Si.

In similar fashion, examination of the element/Al ratios for the other elements reveal that: N/Al, Ni/Al, Cu/Al, and Zn/Al ratios from Group III are considerably elevated (> 2X) over ratios for the river samples; Ca/Al, Cr/Al, Mn/Al, and Fe/Al ratios are moderately (l-2X) elevated over ratios for the river samples; and K/Al and Ti/Al ratios are virtually the same as the ratios for the river samples. These data are taken as evidence for concentration of N, Ca, Cr, Mn, Fe, Ni, Cu, and Zn in biogenic phases in offshore waters. These results are consistent with the general conclusion of Wallace et al., (1977) that biogenic ❑atter regulates the concentrations of particulate metals in offshore surface waters where aluminosilicate concentrations are low.

Table 3 also summarizes the elemental composition of suspended matter samples taken from 5 m above the bottom. With the exception of particulate C and N, the major and trace elements in the near-bottom suspended matter have about the same concentration as the river samples. These data suggest that the coastal rivers, which are the major source of the near-shore surface suspended matter, are also the major source for the near-bottom material. As stated by Feely et al., (1979), this is caused by a number of processes, including: offshore transport and subsequent sinking of near-shore surface material captured by gyres; downwelling and offshore transport of near-shore surface material in winter; and resuspension and offshore transport of previously deposited sediments.

6.2 Lower Cook Inlet

6.2.1 Particulate Matter Distribution and Transport

Figures 18 through 22 show the distribution of suspended matter at the surface and 5 m above the bottom for the April and July 1977 cruises in lower Cook Inlet and Shelikof Strait. As shown in figures 18, 20, and 22, the surface particulate matter distributions are characterized by unusually high horizontal gradients. On the eastern side particulate concentrations were relatively low, ranging from 0.5 mg/L near Cape Elizabeth to about 5.0 mg/L near Cape Ninilchik. On the western side suspended loads increased rapidly from concentrations around 5.0 mg/L in the vicinity of Kamishak Bay to concentrations greater than 100 mg/L north of Tuxedni Bay. The salinity and temperature data for these cruises show very similar horizontal distribution patterns, illustrating the predominance of the inflowing relatively clear saline Gulf of Alaska water on the eastern side and the outflowing turbid low salinity water from upper Cook Inlet on the western side. The outflowing turbid water is transported to the southwest past Augustine Island and Cape Douglas into Shelikof Strait where it continues to mix with the oceanic water and the suspended matter is dispersed. The near-bottom suspended matter distributions (figs. 19 and 21) are very similar to the surface distributions, suggesting that cross-channel gradients in the suspended matter distributions exist throughout the water column.

The seasonal data show some characteristic patterns which apparently are consistent from year to year. First, the outward-flowing brackish water on the western side is colder in May 1978 and warmer in August-September than the inward-flowing Gulf of Alaska water (Feely and Massoth, in press). This feature is consistent with data obtained in April and July 1977 (figs. 18 and 20) and May 1979, and appears to be related to the temperature of the

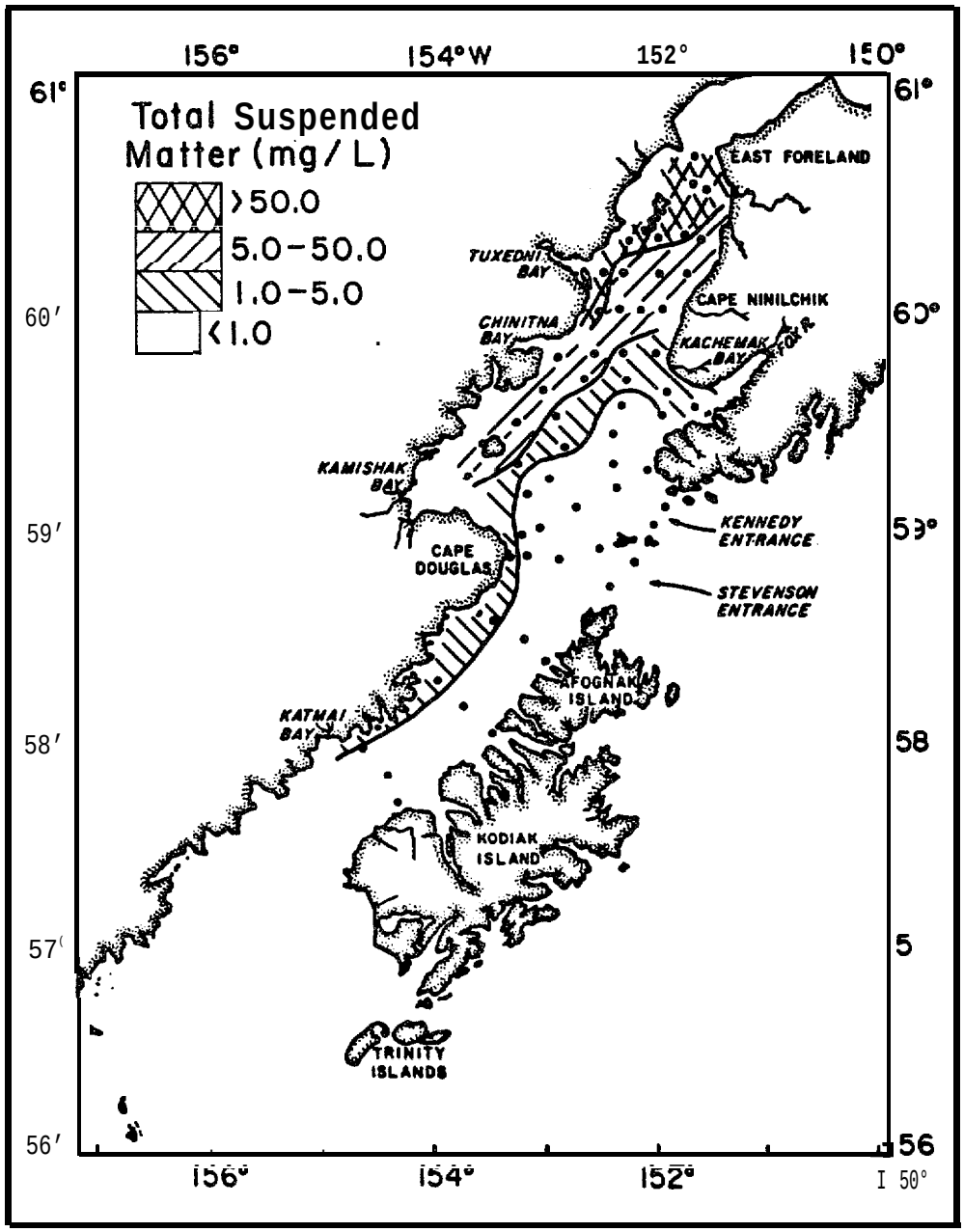

Figure 18. Distribution of total suspended matter at the surface (Cruise RP-4-Di-77A-IV, 4-16 April 1977).

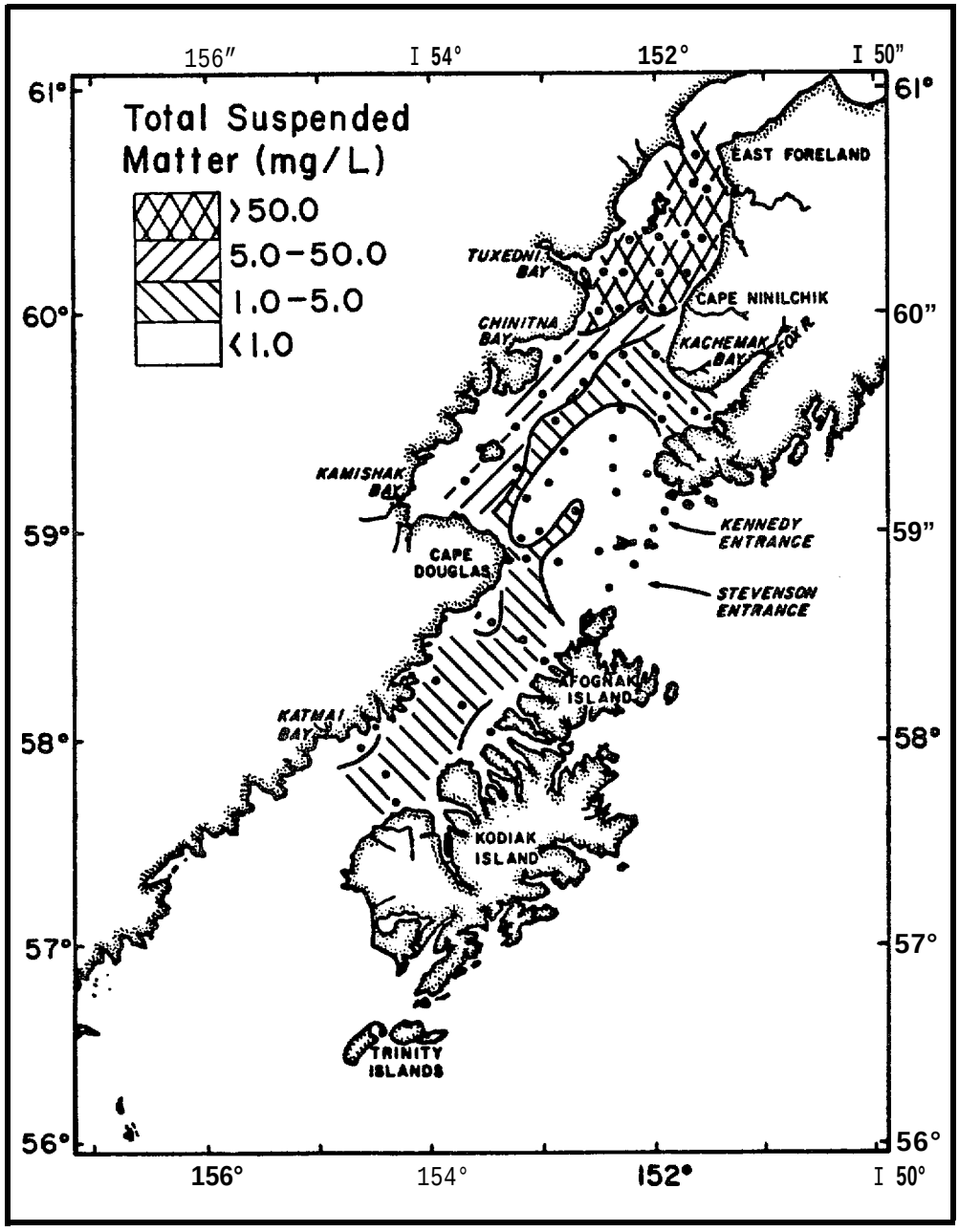

Figure 19. Distribution of total suspended matter at 5 m above the bottom (Cruise RP-4-Di-77A-IV, 4-16 April 1977).

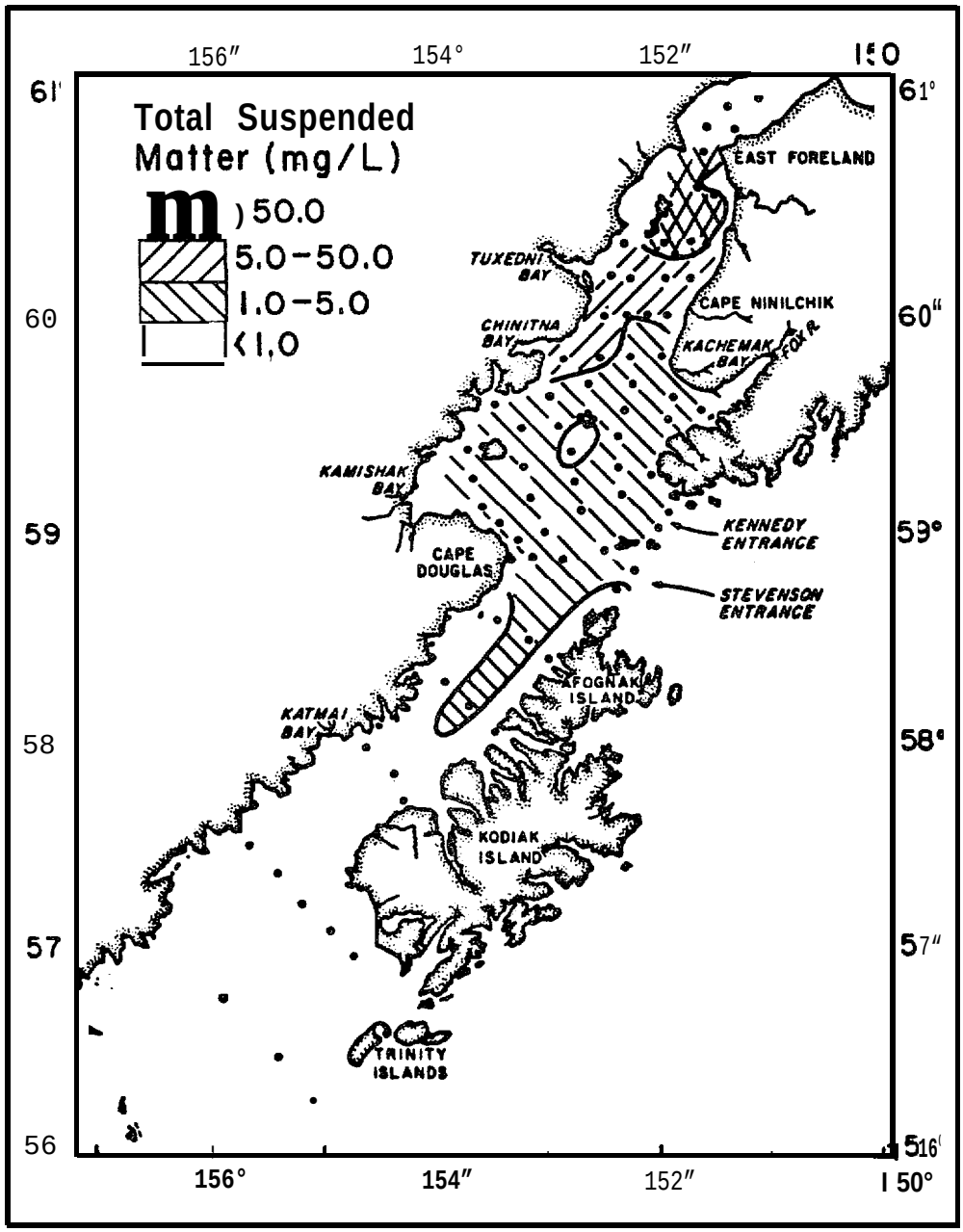

Figure 20. **Distribution of total suspended matter at the surface (Cruise** Acona-245, **28 June - 12 July 1977).**

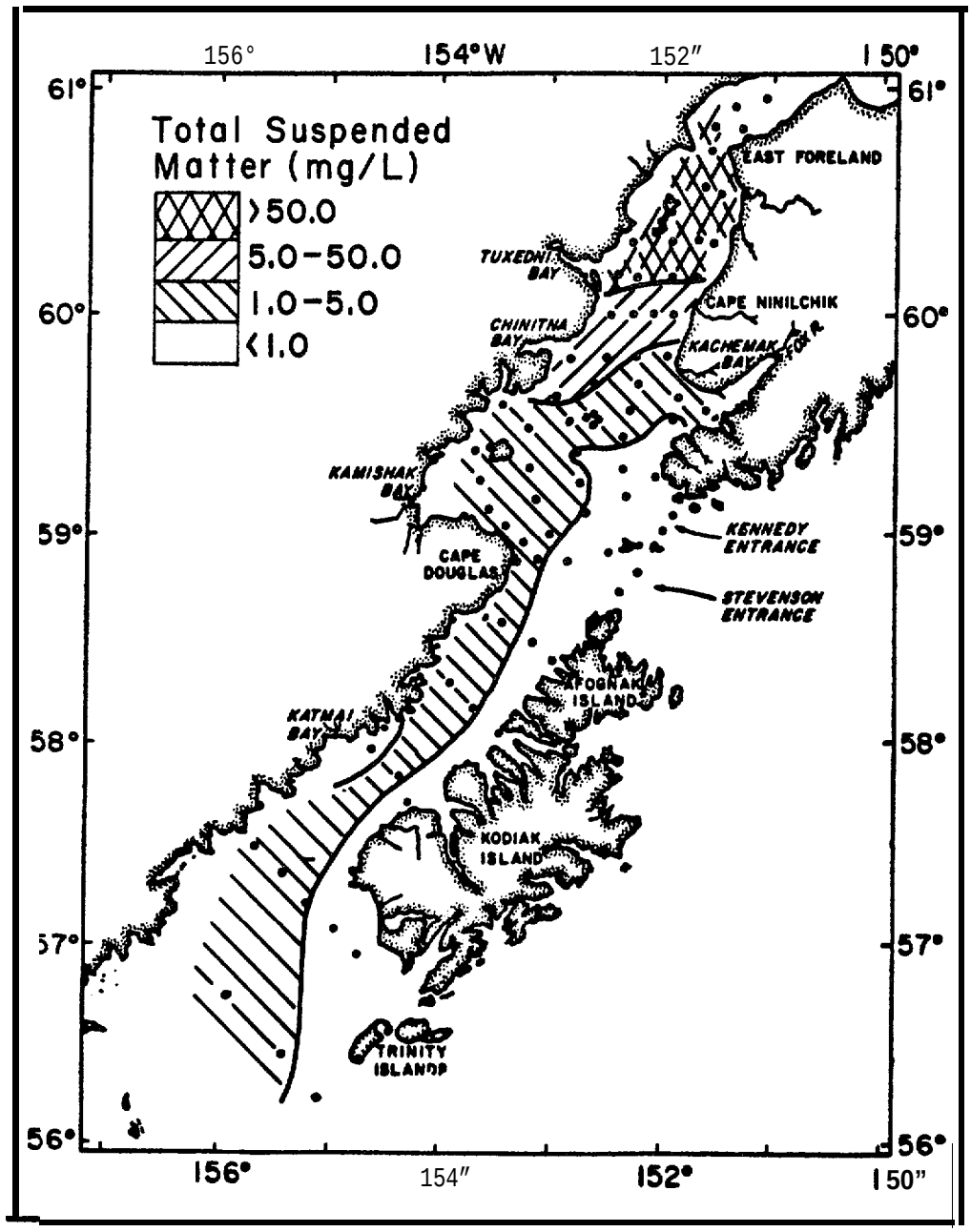

Figure 21. Distribution of total suspended matter at 5 m above the bottom (Cruise Acona-245, 28 June - 12 July 1977).

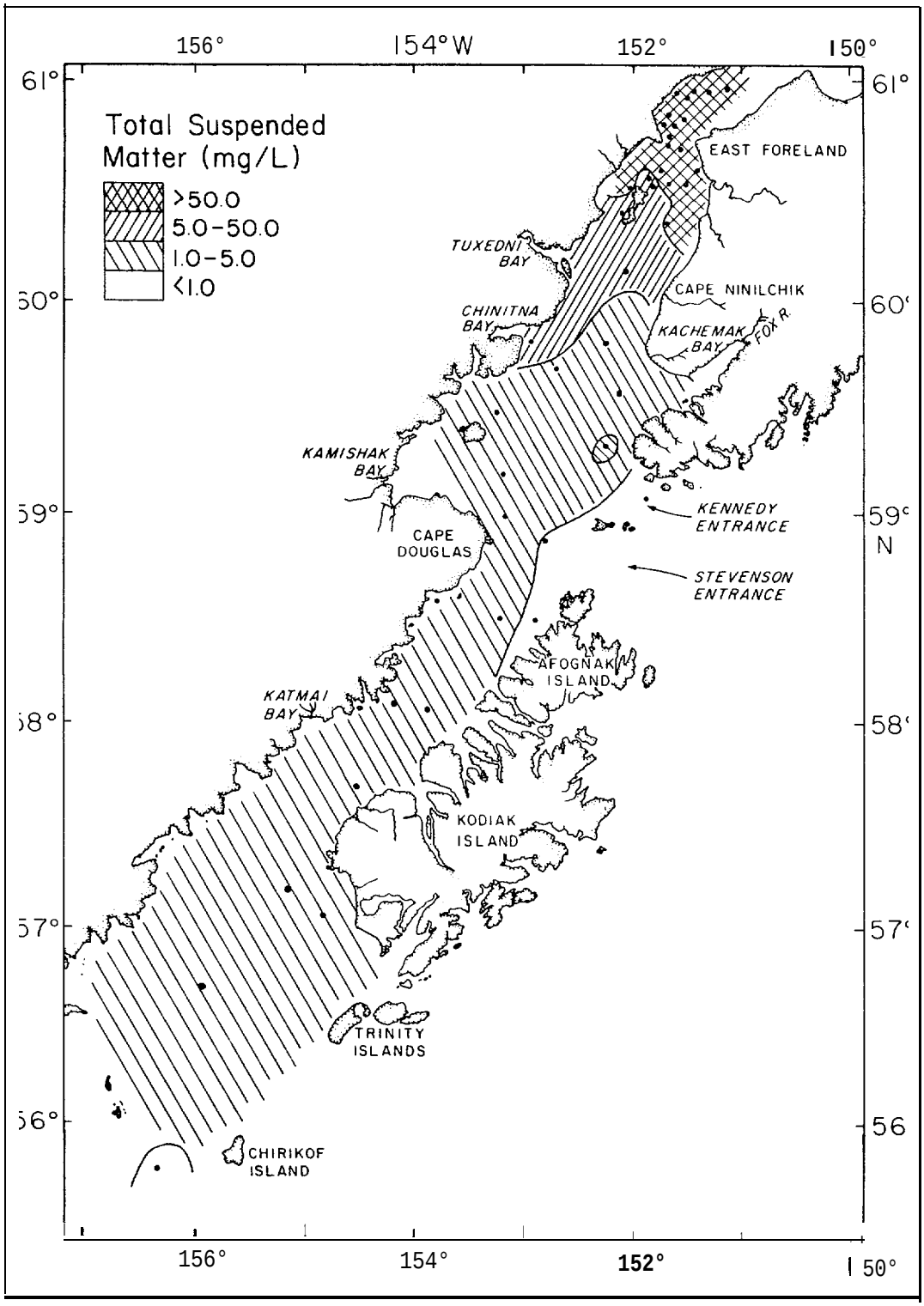

Figure 22. Distribution of total suspended matter at the surface (Cruise RP-4-Di-79A-II, 7-20May 1979).

the in-flowing river water and shows larger seasonal variations due to the larger fluctuations of temperature over the continental land masses. Furthermore, suspended-matter concentrations in the Kamishak Bay region are higher in early spring than in late summer even though there is more freshwater input into Cook Inlet during late summer (Gatto, 1976). A possible explanation for this phenomenon is that early spring is usually the time when most of the ice breakup occurs in upper Cook Inlet. Resuspension and transport of previously deposited sediments may result from the ice movement. Another possibility is that if the currents are strong, there is less time for mixing and dilution of ambient suspended matter. This probably is true to some degree as the April 1977 data show higher suspended matter concentrations and lower salinities than the May 1978 data (Feely and Massoth, in press). However, this cannot be the only explanation because the July and October 1977 data show relatively low suspended matter concentrations (<2.0 mg/L) in Kamishak Bay waters without extensive mixing with seawater (i.e., salinity ≅ 300/00). Nevertheless, the data suggest that more river-borne suspended matter is transported out of the inlet and into Shelikof Strait during early spring than during the summer.

Above the Forelands, suspended matter concentrations range from 120 mg/L starting at about the Forelands (fig. 22) to values greater than 1000 mg/L near the mouths of the Susitna River and Knik Arm (Sharma et al., 1974). Suspended matter distributions in this region are totally dependent upon input from the rivers and tidal mixing. Sharma (1979) states that the amount of suspended matter varies considerably throughout the Foreland region during each tidal cycle, with significant quantities of suspended material being carried south of the Forelands during ebb tide.

Since suspended matter may play an important role in scavenging and transporting contaminants from the study region, the question of where the large amount of suspended materials that pass into lower Cook Inlet ultimately reside becomes important. The dramatic decrease in suspended loads from > 100 mg/L near the Forelands to < 1.0 mg/L near the inlet's mouth may be an indication of particulate settling. However, recent studies of major sediment types in lower Cook Inlet indicate that the sediments in the central part of the inlet consist primarily of unconsolidated coarse-grained sands deposited during the retreat of the Pleistocene glaciers (Bouma and Hampton, 1976). Another possibility is that the suspended matter gradients are the result of dilution of the brackish water by the less turbid oceanic water. Figure 23 shows a scatter plot of the relationship between total suspended matter and salinity for the surface samples from the central region of lower Cook Inlet, where the cross-channel gradients are highest. The data, which were from the April 1977 cruise, show that the suspended loads are linearly correlated with salinity, indicating that dilution is the major process controlling suspended matter concentrations in the central portion of the inlet. A scatter plot for the July 1977 data shows similar results. These results suggest that the central part of lower Cook Inlet acts like a conduit, allowing large amounts of suspended ❑aterial to pass through the system with little net sedimentation. Sedimentation of suspended matter is occurring in the numerous small embayments along the coast.

Figures 24 and 25 show vertical cross-sections of temperature, salinity, total suspended matter, and sigma-t for stations located in Shelikof Strait. The data were obtained on the August-September cruise. Stations SS2, SS5, ss6, SS8, SS9, SS1O, and SS12 represent a longitudinal cross-section along the axis of the Strait. Stations SS4 through SS6 and SS11 through SS13 represent

transverse cross-sections at midchannel and at the upper mouth, respectively. The data show cross-channel gradients of temperature, salinity, and suspended matter which are consistent with the cross-channel gradients in lower Cook Inlet. This is the strongest evidence to date which suggests that riverborne suspended matter from Cook Inlet is transported into Shelikof Strait. There is also evidence for a near-bottom nepheloid layer in the strait which exists in the lower 50-60 m of the water column. Since there are no corresponding large changes in temperature and salinity which would tend to buoy up suspended material, the bottom nepheloid layer in this region is probably due to resuspension of bottom sediments. This suggests that sediments and/or contaminants probably get redistributed in the strait before final deposition occurs.

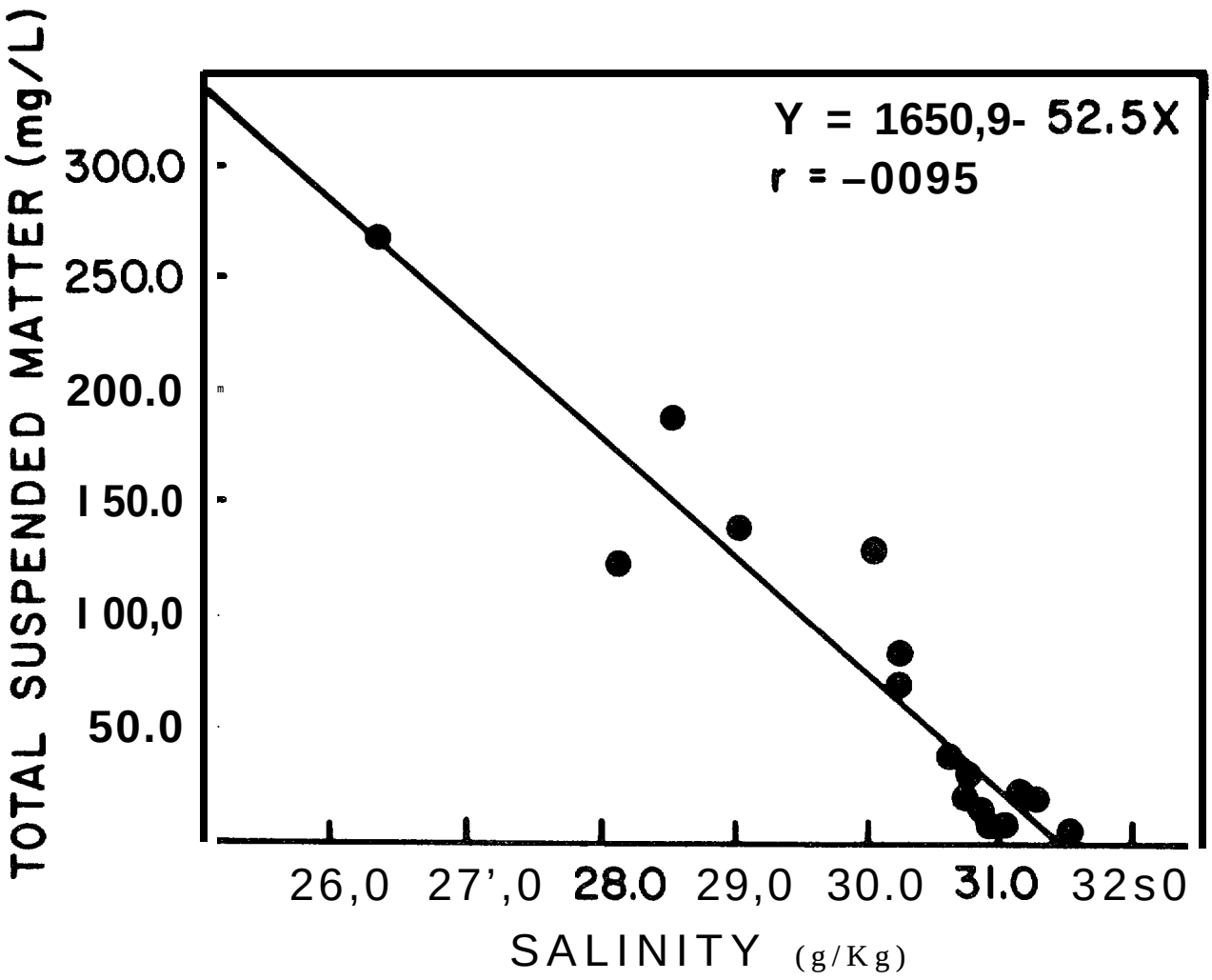

Figure 23. Scatter plot of the relationship between total suspended matter and salinity for surface samples from lower Cook Inlet (Cruise RP-4-Di-77A-IV, 4-16 April 1977).

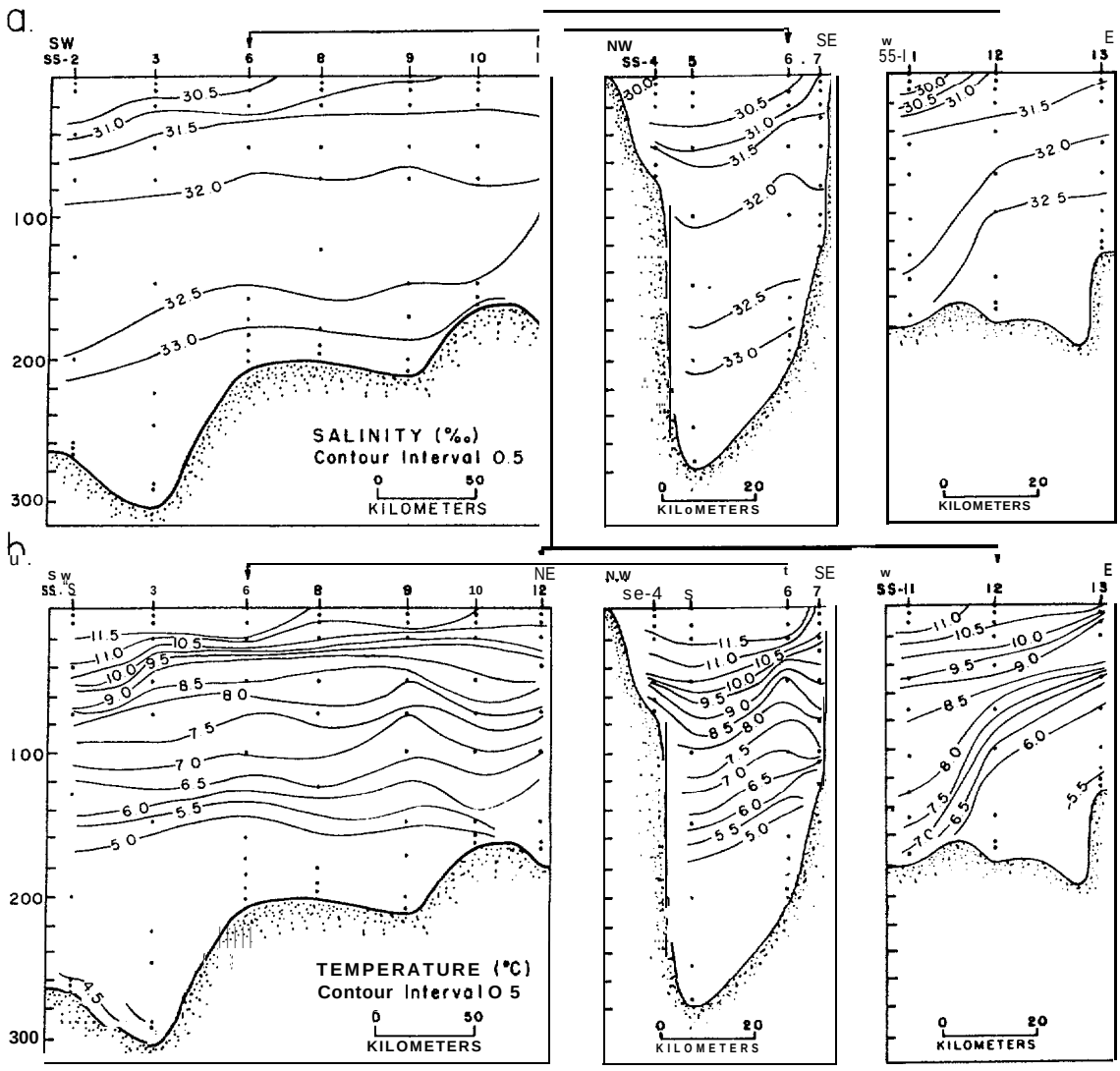

Figure 24. Vertical cross-sections of the distributions of: a. salinity; and b. temperature for stations SS-2 thru SS-13 in Shelikof Strait (Cruise RP-4-Di-78B-II, 22 August - 6 September 1978).

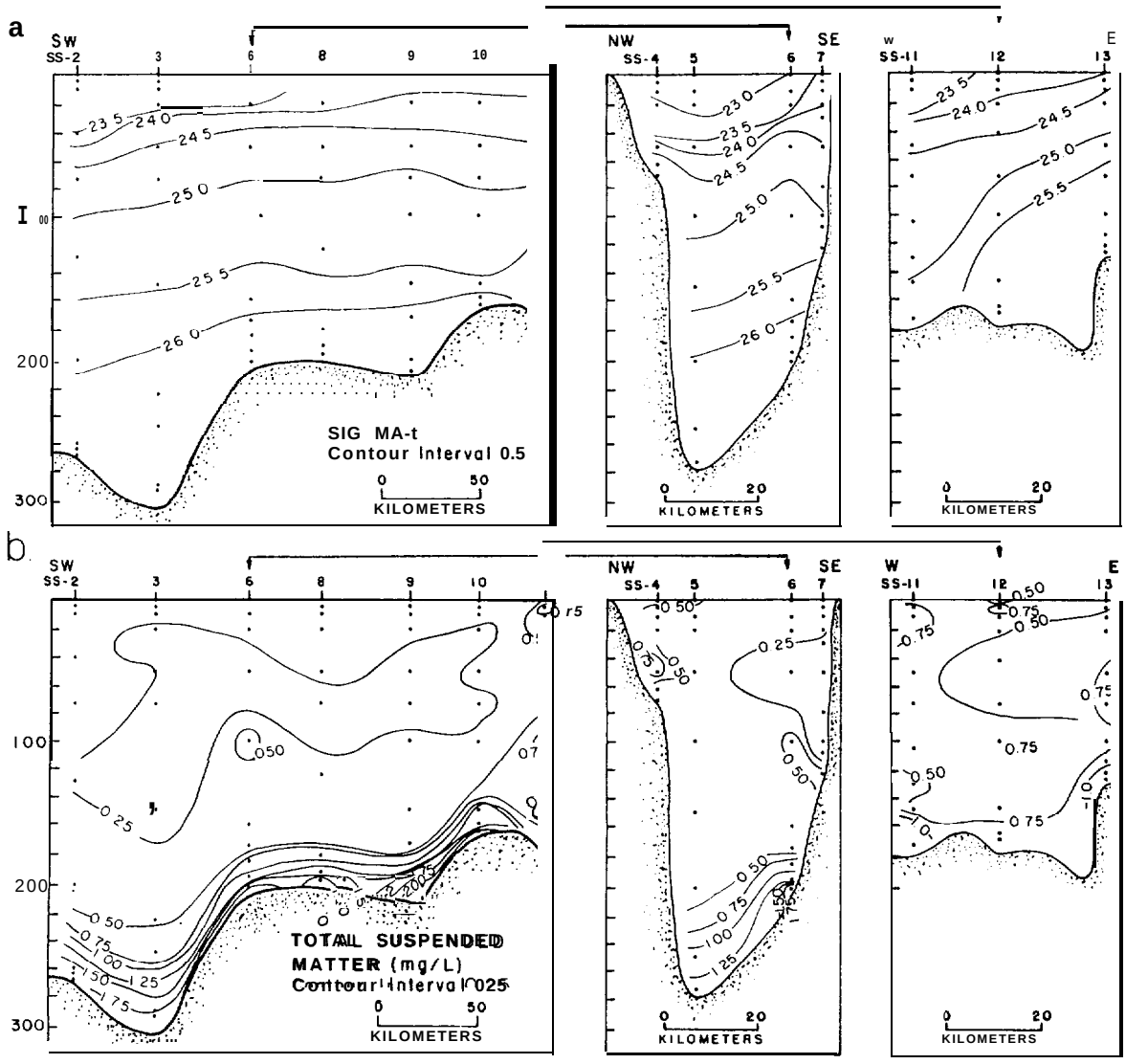

Figure 25. Vertical cross-sections for the distributions of: a. sigma-t; and b. total suspended matter for stations SS-2 thru SS-13 in Shelikof Strait (Cruise RP-4-Di-78B-II, 22 August - 6 September 1978).

6.2.2 Sedimentation Studies

During Cruise RP-4-MF-78A-11 (19 May-4 June 1978), three moorings, each supporting one set of tandem sediment traps located 10 m above the bottom, were deployed along a transect line extending from Kamishak Bay to Kachemak Bay in lower Cook Inlet (fig. 5). The purpose of the traps was to obtain long-term averages of the vertical fluxes of suspended matter in selected regions of lower Cook Inlet. The sediment trap capture period was set for closure approximately 85 days after deployment, which occurred on 27 May 1978. Of the six sediment traps deployed, four were recovered. The two sediment traps from station ST-3 were accidentally dredged up by the fishing vessel, Columbian, and the samples were lost. In addition, one sample from the sediment traps at ST-2 was also lost due to breakage of the sodium azide diffusion cup during recovery. Table 6 summarizes the particulate matter fluxes obtained by gravimetric analysis of the material captured by the traps. Also included are the mean particulate fluxes obtained by Larrance (1978) for short-term sediment trap deployments at CB-1, CB-4, and CB-7. The long-term flux at ST-1 is about the same as the mean value obtained by Larrance for traps deployed at CB-1 (20.8 gin-z d-l vs. 22.0 g $m^{-2} d^{-1}$). This suggests that the two locations are very similar in their sedimentation characteristics and the data from the two sets of traps can be intercompared. The long-term sediment flux at ST-2 was 2.4 times greater than the mean of the sediment fluxes at CB-4 (28.5 g m^{-2} d-' VS. 12.0 g $m^{-2} d^{-1}$). While these stations were less than 15 nautical miles apart (fig. 5), these differences are probably real because station ST-2 is within the region dominated by the outward-flowing brackish water and station CB-4 is in the region influenced by the inward-flowing Gulf of Alaska water. Presumably, a significant fraction of the suspended matter in the outward-

TABLE 6. Comparison of sedimentation rates of suspended materials collected by sediment traps deployed on moorings approximately 10 m above the bottom at selected locations in lower Cook Inlet with average accumulation rates of the underlying sediments as determined by ^{210}Pb geochronology.

Location	Station No.	Average Sedimentation Rate of Suspended Matter (gi^{n-2} d-l)	Average Accumulation Rate of Sediments (gi^{n-2} d^{-1})
Kamishak Bay	CB-1*	22.0 ± 25	27.1
	ST-1	20.8 ± 7	2.2
Central Inlet	CB-4*	12.0 ± 8	no data
	ST-2	28.5	no data
Kachemak Bay	CB-7*	18.8 ± 2	10.5

*After Larrance and Chester (1979).

flowing brackish water settles out in Kamishak Bay. These data are consistent with the ^{210}Pb sediment accumulation rates for the underlying sediment cores (table 6). The good agreement between the sedimentation rate and the sediment accumulation rate for CB-1 in Kamishak Bay indicates that this region is a depositional environment for the fine-grained material that originates from upper Cook Inlet.

In order to obtain a more detailed picture of the long-term sedimentation history of fine-grained sediments in lower Cook Inlet and Shelikof Strait, sediment cores were collected during three of the cruises for ^{210}Pb geochronological studies. The locations of the gravity cores obtained are illustrated in fig. 26. The cores were cut into 2-cm sections and delivered to C.W. Holmes and E.A. Martin (U.S. Geological Survey, Corpus Christi, Texas) who performed the ^{210}Pb analyses. No cores were collected from the central basin of lower Cook Inlet although numerous attempts were made. The sediments there are primarily composed of relict sands and gravels (Bouma and Hampton, 1976) which did not remain intact during recovery of the gravity corer. The results of the ^{210}Pb radiometric analyses are given in table 7. The data show that the major regions of sedimentation in decreasing order of importance are: Shelikof Strait, Kamishak Bay, and Kachemak Bay. Using the sediment distribution map of Bouma and Hampton (1976) for lower Cook Inlet, it is estimated that the areas of active sedimentation are 750 km^2 in Kamishak Bay and 60 km^2 in Kachemak Bay. Averaging the ^{210}Pb sediment accumulation rates for these two regions (i.e., 0.66 g cm^{-2} y^{-1} in Kamishak Bay and 0.38 g cm^{-2} y^{-1} in Kachemak Bay) and multiplying by the area of active sedimentation yield estimates of annual sediment accumulations of 4.9×10^{12} g y^{-1} and 2.3×10^{11} g y^{-1}, respectively, for these two regions. This represents only about 18% of the total annual input of fine-grained sediments to Cook Inlet from the rivers

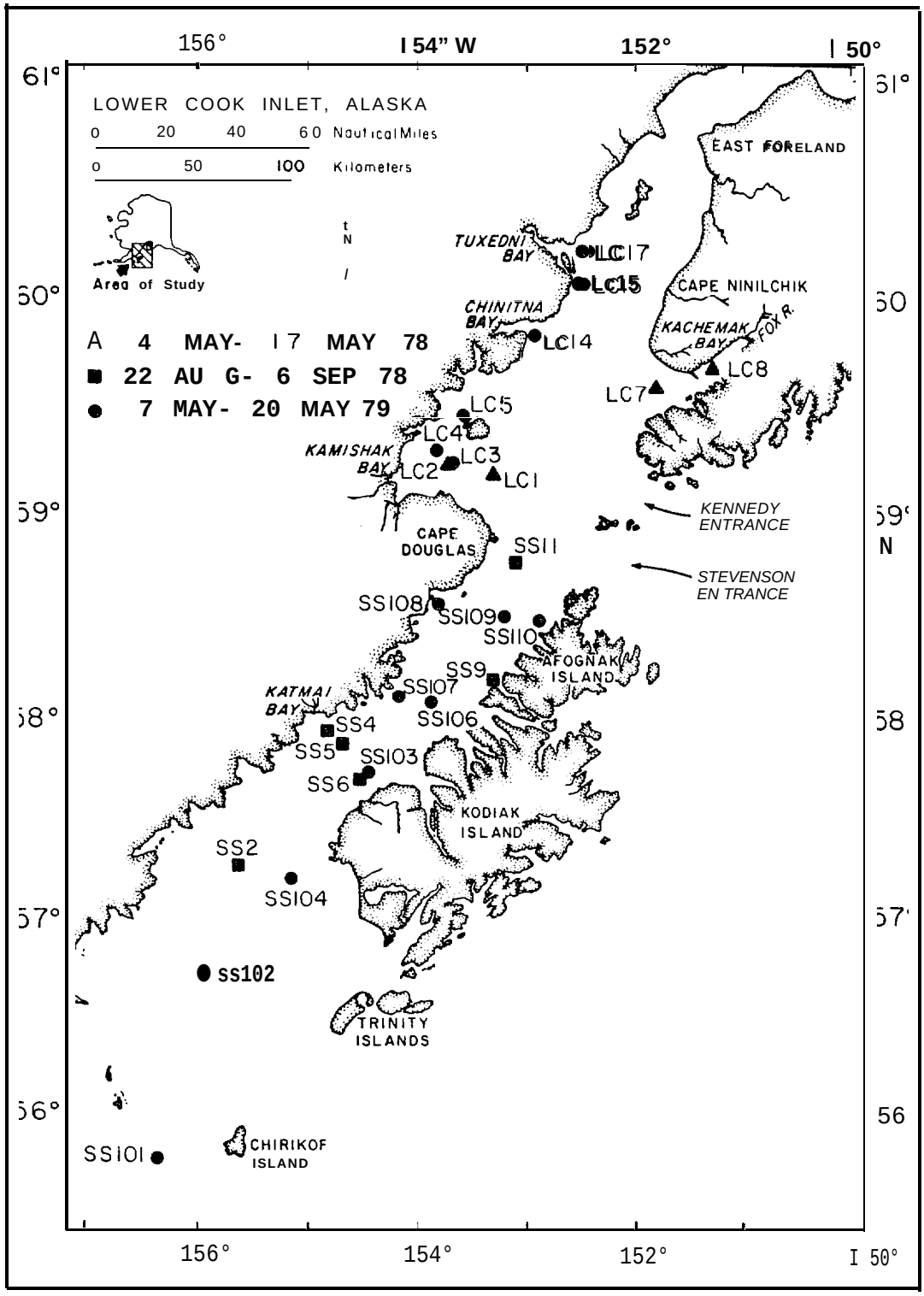

Figure 26. **Locations of stations where gravity cores have been collected for the determination of excess ^{210}Pb activity.**

estimated to be approximately 2.8 x 10^{13} g y-l, Gatto, 1976; Sharma, 1979). The remaining 82% must either be deposited in upper Cook inlet or transported in Shelikof Strait. Since the sediments of upper Cook Inlet also consist primarily of relict sands and gravels (Sharma and Burrell, 1970; Sharma et al., 1979), we believe that the major fraction of fine-grained sediments that originates in Cook Inlet is transported to Shelikof Strait where it is deposited. This conclusion is supported by ^{210}Pb data for Shelikof Strait. Using the 100 m contour as the upper limit of the region of active sedimentation in the upper third of the Strait and the 200 m contour as the upper limit of the region of active sedimentation in the lower Strait, an area of 9200 km^2 is estimated to be the region of active sedimentation. This region was divided into three sections and average accumulation rates were computed for each (i.e., 0.8 g cm^{-2} y^{-1} for the upper third; 0.7 g cm^{-2} y^{-1}; for the middle third; and 0.6 g cm^{-2} y^{-1} for the bottom third). Multiplying the sediment accumulation rates by the respective areas and obtaining the sum yields an estimate of the annual sediment accumulation rate of 6,2 x 10^{13} g Y^{-1} for Shelikof Strait between Cape Douglas and the Trinity Islands. This value is approximately 220% of the annual input of fine-grained sediments from the rivers discharging into Cook Inlet. This suggests that additional sources of fine-grained sediments are required to balance this accumulation rate. The recent findings of Feely and Massoth (in press) indicate that suspended sediments in Shelikof Strait consist of a mixture of clay-sized suspended material from Cook Inlet, terrigenous sediments from the Copper River in the northeast Gulf of Alaska, and biogenic material produced in the water column. If these materials form the bulk of the fine-grained sediments in Shelikof Strait then the sedimentological data presented here would indicate that the sediments of Shelikof Strait are probably composed of nearly a 40:60 mixture of Cook Inlet-derived material and Copper River-derived material.

Table 7. Sediment accumulation rates for sediment cores collected from lower Cook Inlet and Shelikof Strait. Accumulation rates were determined by the excess ^{210}Pb method.[1]

Station No.	Position	Depth (m)	Core Acquired Month/Year	Accumulation Rate ($g\ m^{-2}\ d^{-1}$)
SS101	55°46.8'N, 156°22.1'W	245	May 1979	DNA[2]
SS102	56°42.8'N, 155°56.7'W	292	May 1979	16.7
SS104	57°11.2'N, 155°07.8'W	225	May 1979	DNA
SS2	57°17.1'N, 155°37.0'W	278	Sept.1978	DNA
SS4	57°55.3'N, 154°48.4'W	152	Sept.1978	DNA
SS5	57°52.1'N, 154°42.9'W	273	Sept.1978	17.8
SS6	57°42.4'N, 154°29.1'W	208	Sept.1978	20.3
SS103	57°43.0'N, 154°26.7'W	208	May 1979	16.7
SS106	58°03.5'N, 153°51.7'W	194	May 1979	37.2
SS107	58°05.2'N, 154°09.2'W	285	May 1979	DNA
SS9	58°11.3'N, 153°21.1'W	210	Sept.1978	DNA
SS108	58°32.9'N, 153°47.2'W	51	May 1979	22.5
SS109	58°28.9'N, 153°12.9'W	168	May 1979	8.8
SS110	58°28.2'N, 152°53.6'W	192	May 1979	DNA
Ssll	58°46.4'N, 153°08.3'W	186	Sept.1978	NA[3]
LC 1	59°11.5'N, 153°19.2'W	38	May 1978	2.2
LC2	59°14.4'N, 153°40.9'W	33	May 1978	27.1
LC3	59°13.4'N, 153°40.7'W	35	May 1979	DNA
LC4	59°16.4'N, 153°50.6'W	24	May 1979	9.3
LC5	59°25.6'N, 153°35.5'W	26	May 1979	DNA
LC7	59°34.1'N, 151°37.1'W	79	May 1978	10.4
LC8	59°39.3'N, 151°16.7'W	30	May 1978	5.2
LC14	59°46.9'N, 152°55.5'W	27	May 1979	DNA
LC15	60°03.5'N, 152°28.4'W	30	May 1979	DNA
LC17	60°14.2'N, 152°23.6'W	48	May 1979	NA

[1] Data prepared by C. W. Holmes and E. A. Martin, U.S.G.S. , Corpus Christi, Texas

[2] DNA - data not available

[3] NA - no excess ^{210}Pb detected

6.2.3 Elemental Composition of the Particulate Matter

The particulate matter collected during the six cruises in lower Cook Inlet have been analyzed using a variety of methods to determine how the elements are distributed in the particles. Total elemental composition of the particulate matter was determined by the x-ray fluorescence and atomic absorption techniques described in section 5 of this report. Trace elements associated with the easily oxidizable organic matter and manganese oxyhydroxide coatings were determined on selected samples from 1978 time series stations at CB-7, CB-9, and CB-10. The results of these studies are described below.

Tables 8 through 10 compare summaries of the data on the total elemental composition of suspended matter from the Susitna, Knik, and Matanuska Rivers with summaries of the surface and near-bottom data for the April and July 1977 cruises in lower Cook Inlet. Within the statistical limits of the measurements, the samples from lower Cook Inlet have very nearly the same major element composition as the samples from the rivers. This is especially true for Al, K, Ti, and Fe which have been shown to be almost exclusively associated with aluminosilicate minerals of terrestrial origin (Price and Calvert, 1973). The high concentrations of these elements in the surface and near-bottom samples from lower Cook Inlet indicate that aluminosilicate minerals are the most dominant (80-95%) solid phase in the particulate matter.

These results are not surprising since the Susitna, Matanuska and Knik Rivers supply about $15\text{-}20 \times 10^6$ tons of sediment annually to the inlet (Rosenberg and Hood, 1967).

Table 8. Summary of the elemental composition of particulate matter samples from the ❑ajor rivers discharging into Cook Inlet. (Surface samples were obtained with a precleaned 4-L polyethylene bottle extended from a bridge 26 June 1977.)

Element	Susitna River	Matanuska River	Knik River
c (Wt.%)	1.04	0.55	0.75
N (Wt.%)	0.06	0.03	0.05
Mg (Wt.%)	4.28	3.02	4.30
Al (Wt.%)	10.39	8.57	12.90
Si (Wt.%)	36.12	28.53	36.32
K (Wt.%)	2.62	1.54	2.73
Ca (Wt.%)	2.33	2.37	1.33
Ti (Wt.%)	0.63	0.55	0.67
Cr (ppm)	172	112	182
Mn (ppm)	1308	1157	1206
Fe (Wt.%)	6.45	6.07	6.90
Ni (ppm)	94	43	70
Cu (ppm)	71	49	61
Zn (ppm)	186	106	152
Pb (ppm)	56	25	51

Table 9. Summary of the elemental composition of particulate matter samples from lower Cook Inlet (Cruise RP-4-Di-77A-IV, 4-16 April 1977).

Element	Average of 50 surface samples	Average of 50 samples from 5 m from the bottom
c (Wt.%)	4.01 ± 4.0	2.72 ± 2.5
N (Wt.%)	0.65 ± 0.5	0.41 ± 0.4
Mg (Wt.%)	3.54 ± 0.6	3.47 ± 0.9
Al (Wt.%)	3.64 ± 1.6	8.70 ± 1.6
Si (Wt.%)	31.04 ± 3.4	30.20 ± 4.3
K (Wt.%)	2.15 ± 0.4 .	2.24 ± 0.4
Ca (Wt.%)	2.20 ± 0.4	2.23 ± 0.3
Ti (Wt.%)	0.55 ± 0.1	0.58 ± .07
Cr (ppm)	95 ± 15	99 ± 16
Mn (ppm)	1313 ± 113	1326 ± 159
Fe (Wt.%)	6.22 ± 1.0	6.42 ± 0.8
Ni (ppm)	61 ± 10	63 ± 10
Cu (ppm)	71 ± 15	76 ± 17
Zn (ppm)	165 ± 32	176 ± 34
Pb (ppm)	56 ± 13	56 ± 12

Tables 9 and 10 also summarize the elemental composition of 50 samples taken 5 m above the bottom. In general, the major element concentrations of the near-bottom samples are similar to the surface samples. This is especially true for the April 1977 cruise and in the northern part of the inlet where the water column is well mixed. However, during the July 1977 cruise and in the southern part of the inlet the water column was vertically stratified and the elemental composition of the suspended matter showed some differences between the surface and 5 m above the bottom. For example, figure 27 shows vertical cross-sections of particulate C and C/N ratios for the May and August-September 1978 cruises. The August-September data show higher particulate C concentrations at the surface than at the bottom, indicating a vertical stratification of the particulate organic matter. Similar vertical gradients are not easily discernible in the May 1978 or April 1977 data which suggests that in early spring the waters are extremely well-mixed with respect to water properties and suspended matter.

The vertical cross sections of particulate C also show significant cross channel gradients in both spring and summer data, with the highest concentrations and vertical gradients occurring at stations located in Kachemak Bay. Larrance et al. (1977) state that phytoplankton productivity and standing stocks of chlorophyll a are highest in Kachemak Bay and decrease steadily to low values in the middle of the inlet. These data suggest that the observed variations of particulate C are directly related to production of marine organic matter in the inlet, with Kachemak Bay being the most productive. This is probably the result of a number of factors, including: (1) upwelling of nutrient-rich subsurface waters in the region northwest of the Chugach Islands (Burbank, 1977); (2) stratification and stabilization of the surface waters due to formation of two gyre systems (Burbank, 1977 and Larrance et

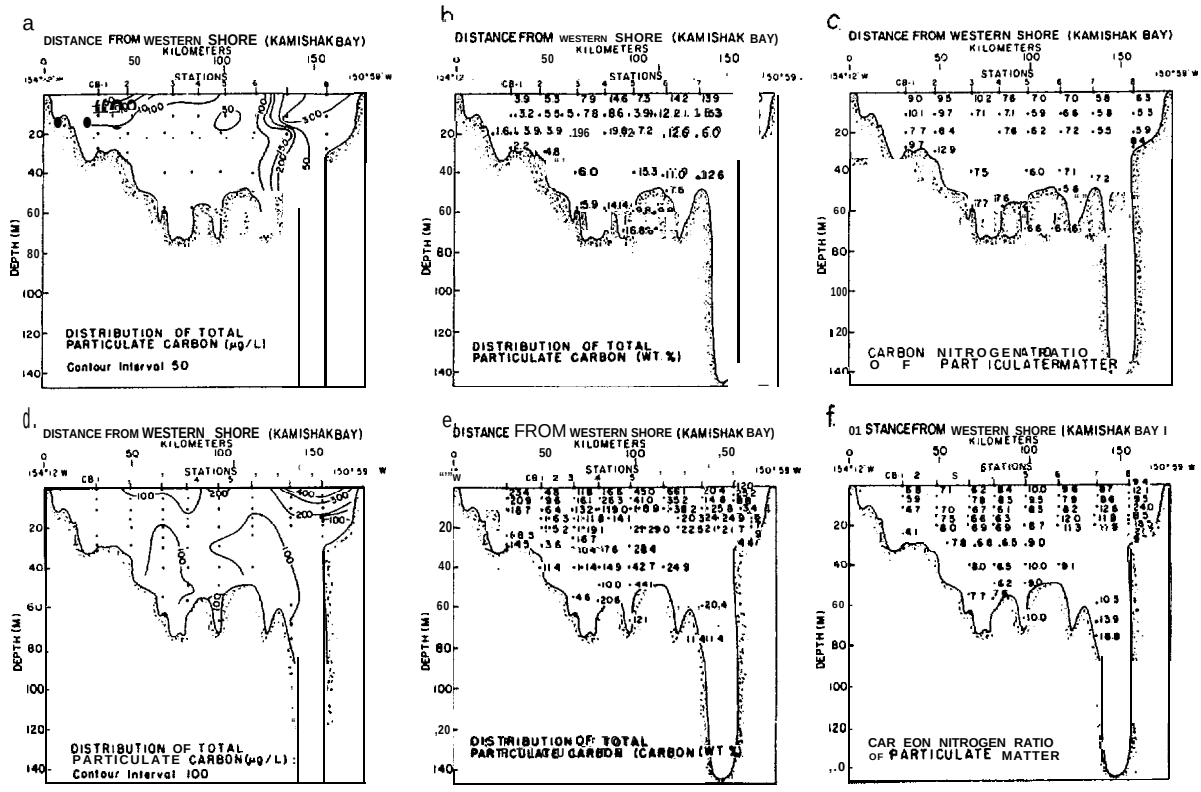

Figure 27. Vertical cross-sections of the distributions of: a. particulate carbon in units of µg/L; b. particulate carbon in weight percent of the suspended matter; and c. carbon to nitrogen atom ratios for stations CB-1 thru CB-8 in lower Cook Inlet (Cruise RP-4-Di-78A-III, 4-17 May 1978).

Table 10. Summary of the elemental composition of particulate matter from lower Cook Inlet and Shelikof Strait (Acona-245, 28 June - 12 July 1977).

Element	Lower Cook Inlet		Shelikof Strait	
	Average of 50 Surface Samples	Average of 51 Samples from 5 m above the Bottom	Average of 17 Surface Samples	Average of 16 Samples from 5 m above the Bottom
C (Wt.%)	10.77 ± 11.0	6.18 ± 9.0	31.17 ± 11.2	8.40 ± 5.8
N (Wt.%)	1.98 ± 2.0	0.99 ± 1.4	4.89 ± 1.5	1.24 ± 0.8
Mg (Wt.%)	2.86 ± 1.41	3.59 ± 0.82	1.89 ± 0.91	4.01 ± 1.22
Al (Wt.%)	6.98 ± 4.24	8.88 ± 2.34	3.72 ± 2.46	9.49 ± 3.20
Si (Wt.%)	35.75 ± 5.56	38.09 ± 4.92	28.67 ± 10.10	44.71 ± 3.60
K (Wt.%)	1.86 ± 0.86	2.24 ± 0.45	0.89 ± 0.43	2.19 ± 0.63
Ca (Wt.%)	1.84 ± 0.63	2.23 ± 0.32	1.53 ± 0.35	2.08 ± 0.33
Ti (Wt.%)	0.46 ± 0.20	0.58 ± 0.10	0.27 ± .09	0.53 ± 0.12
Cr (ppm)	99 ± 30	115 ± 24	75 ± 36	116 ± 29
Mn (ppm)	1138 ± 574	1460 ± 362	981 ± 709	4174 ± 7642
Fe (Wt.%)	5.14 ± 2.11	6.50 ± 0.95	3.15 ± 1.14	6.39 ± 1.71
Ni (ppm)	70 ± 25	81 ± 16	59 ± 19	77 ± 13
Cu (ppm)	99 ± 33	100 ± 31	94 ± 27	112 ± 30
Zn (ppm)	352 ± 158	343 ± 194		
Pb (ppm)	65 ± 19	69 ± 13	60 ± 10	76 ± 22

al., 1977); and (3) deeper light penetration due to input of relatively non-turbid oceanic water from the Gulf of Alaska.

Undoubtedly, some of the organic matter that is produced in the Kachemak Bay region settles to the bottom and gets buried within the sediments. However, since the net circulation is to the north and back again to the southwest into Shelikof Strait, a significant fraction of the organic matter produced in Kachemak Bay probably gets deposited in Shelikof Strait. This means that the two regions are linked by physical, chemical, and biological processes. While detailed information on chemical and biological processes in Shelikof Strait are unavailable at this time, data from the August-September cruise are available which tend to support the hypothesis that the two regions are linked by chemical processes. Figure 28 shows the distributions of particulate C and particulate Mn in Shelikof Strait. The enrichment of particulate Mn in the near-bottom waters is probably due to release of reduced Mn from the sediments. This process occurs in regions of high productivity and high sedimentation (Graham et al., 1976). While data on regional productivity in Shelikof Strait are unavailable at this time, the data suggest that there is a positive correlation between particulate C and Mn in the near-bottom waters and that lower Cook Inlet is probably a major source for the organic matter. Although limited to a great extent, these data indicate that physical and chemical processes occurring in dynamic environments in lower Cook Inlet directly affect bottom water chemistry in the less dynamic environments of Shelikof Strait. If any of these processes are altered, either by natural or artificial means, the major effect might be observed in Shelikof Strait. If this is the case, then environmental parameters monitored in Shelikof Strait may be sensitive indicators of subtle changes occurring in the inlet.

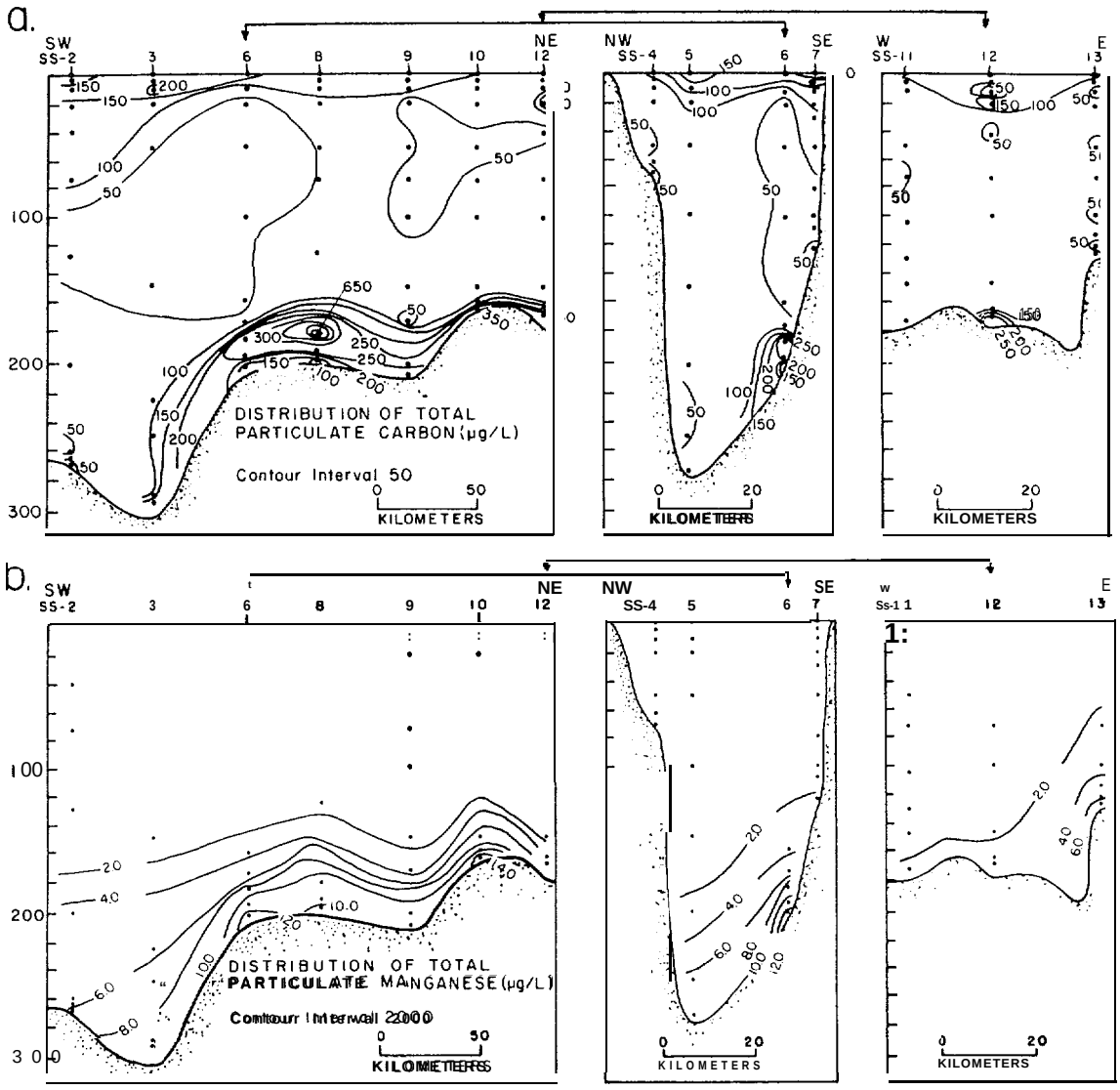

Figure 28. **Vertical cross-sections of the distribution of: a. total particulate carbon; and b. total particulate manganese for stations SS-2 thru SS-13 in** Shelikof **Strait (Cruise** RP-4-Di-78B-II, **22 August - 6 September 1978).**

6.2.4 Extractable Elements in the Particulate Matter

During the May and August-September 1978 cruises, large volume particulate samples were collected on 142 mm Nuclepore filters for the purpose of providing information on the potential availability of trace elements to organisms. Water was collected at the surface and 5 m above the bottom every 12 hours for 48 hours in Kachemak Bay (CB-7) and west of Kalgin Island (CB-9) in May (fig. 5), and east of Kalgin Island (CB-10) in August-September (fig. 6). In addition, a single surface sample was collected in May at CB-1 in Kamishak Bay (fig. 5). The samples were subjected to: (1) a peroxide treatment to release organically bound trace elements; (2) a 0.3 N HCl treatment to release elements associated with Fe-Mn oxyhydroxide coatings on particles; and (3) a total element analysis of untreated samples. A full description of the procedures is provided in section 5.

In contrast to the high degree of temporal variations of particulate material in the water column at CB-9 (Feely and Massoth, in press), the trace element content of the surface particulate material remained fairly constant (fig. 29). The average total elemental composition and the partitioning between organic and oxyhydroxide phase are listed in table 11. The major cation content of the particulate matter from CB-9 suggests that the source of this material was the illite-rich suspended material of the rivers flowing into upper Cook Inlet. The small amount of trace metals present in the peroxide extractable phase reflects the concentration and character of the particulate organic matter. Due to the turbidity associated with the high suspended matter concentrations, the biological productivity in this region is low (Larrance et al., 1977), resulting in organic matter comprising only 2% of the total weight of suspended material. This organic matter has a C/N ratio of 11.3 indicative of a terrestrial origin (Loder and Hood, 1972). Cu showed the highest degree of organic association with 1.7% of the total Cu being present in peroxide

extractable phase, followed by Mn and Cr each with 0.5%. The weak acid extraction released a major portion of the total Fe and Mn demonstrating the amorphous character of these metal oxides. Many of the trace elements were enriched in this component of the suspended matter. An average of 85% and 76% of the total Ni and Cu, respectively, were present in this phase, while half of the Zn and Cr were also present. The residual material, which is comprised of highly crystalline material, contained 90% of the Al and Pb, and a lesser fraction of the other metals. As a consequence of vertical mixing in this region, the elemental compositions and phase associations of the surface and near-bottom suspended matter samples were not significantly different ($p<0.05$). The time-series data at CB-10, east of Kalgin Island in September-August, showed the same constancy in elemental compositions and phase associations (fig. 30). There were no significant differences ($p<0.05$) between surface and near bottom samples in the fall time series. Comparison of the two time-series data in the Kalgin Island region showed no differences in elemental compositions nor phase associations. In summary, the Kalgin Island region is characterized by a highly fluctuating amount of suspended matter of a constant composition. This suspended matter is composed primarily of structured aluminosilicates coated with Fe-Mn oxyhydroxides. With the exception of Pb and Zn, these coatings contain the largest fraction of trace elements in the particulate matter. The small amount of organic matter present is of terrestrial origin and contains less than 2% of the total amount of trace metals present in suspension.

Water originating from the Kalgin Island region flows along the western side of lower Cook Inlet where a major portion is diverted into Kamishak Bay (Muench et al., 1978). Consistent with this observation, the major element

composition of Kamishak Bay suspended material reflects the dominance of illite material similar to that found in upper Cook Inlet. (Feely and Massoth, in press]. However, analysis of a single large volume surface sample from Kameshak Bay shows enrichments of Cr, Cu, Ni, Zn, and Pb relative to that of Kalgin Island (table 12). Although organic matter comprises 6% of the suspended material, the increased amount of metals in the peroxide extractable phase cannot account for the enrichments of the whole sample. Examination of the weak-acid extractable phase suggests that the additional Zn, Cu, and Pb were associated with a weakly structured phase while the additional Cr and Ni were present in a highly crystalline phase. These enrichments are probably due to either resuspension of bottom material or a source of trace metal-enriched illite material transported by local rivers flowing into Kamishak Bay.

Unlike the upper Cook Inlet region, the suspended matter concentration in Kachemak showed smaller fluctuations with time and little difference with depth (fig. 31). However, the fluctuation in elemental composition and phase associations was greater than in upper Cook Inlet and there was significant difference between the composition of surface and bottom material (fig. 31 and table 12). The surface suspended material consisted of 35% organic matter and had a C/N ratio of 7.6, characteristic of a marine origin (Loder and Hood 1972). The remaining material consisted of 40% biogenic SiO_2 and 20% aluminosilicates. The marine origin of this material can also be seen in the trace element composition and phase association data (table 12). The surface suspended matter was depleted in all elements relative to terrestrial aluminosilicates. The Mn concentration of this material was 540 ppm while that of CB-9 was 1300 ppm. The greater organic matter content of the surface material resulted in increase in the amount of trace metal present in the peroxide extractable phase. In the

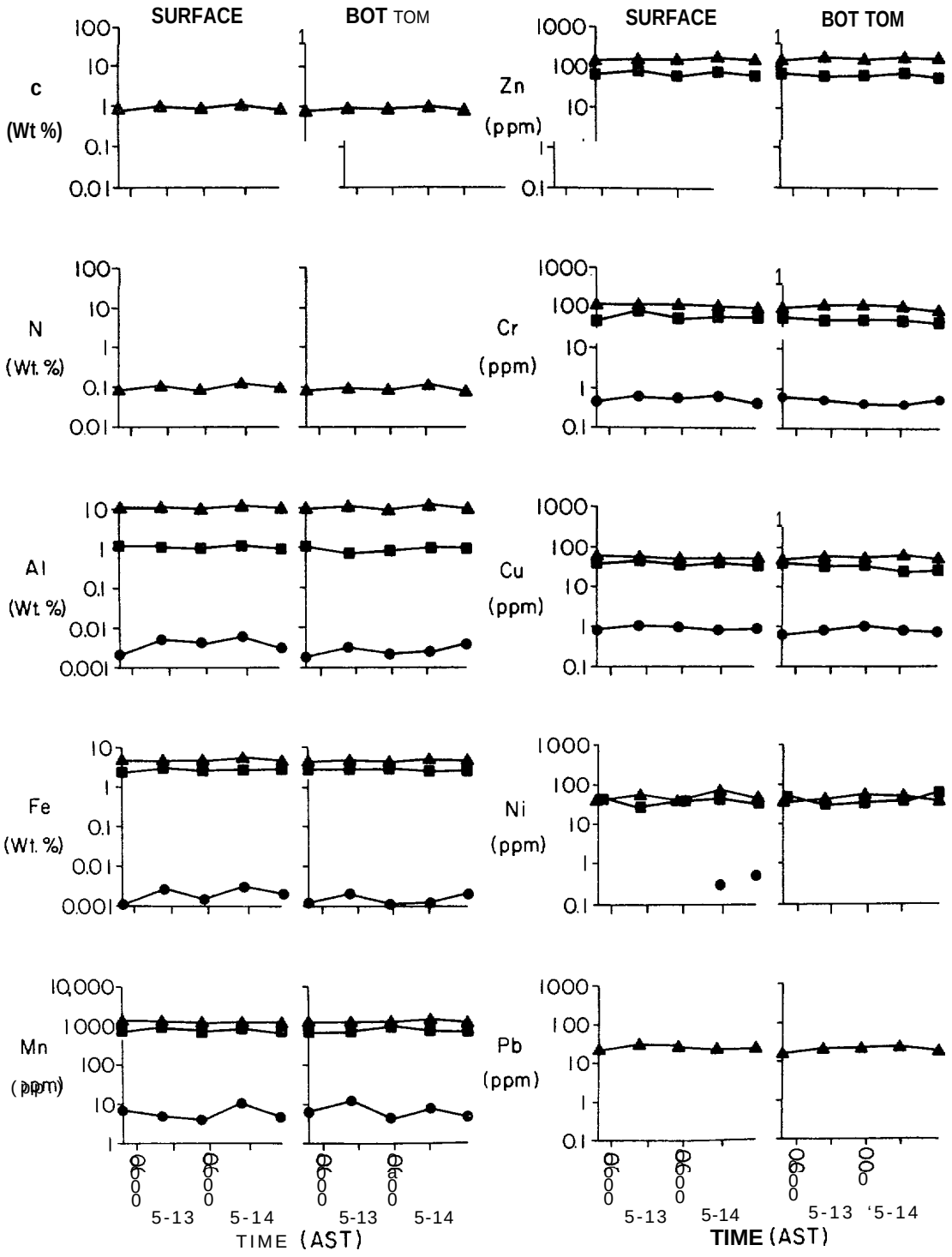

Figure 29. **Temporal variations of major and trace elements in suspended matter (total concentration [A], weak acid extractable [■], and peroxide extractable [●] from station CB-9 in lower Cook Inlet.) Samples were collected 13-14 May 1978.**

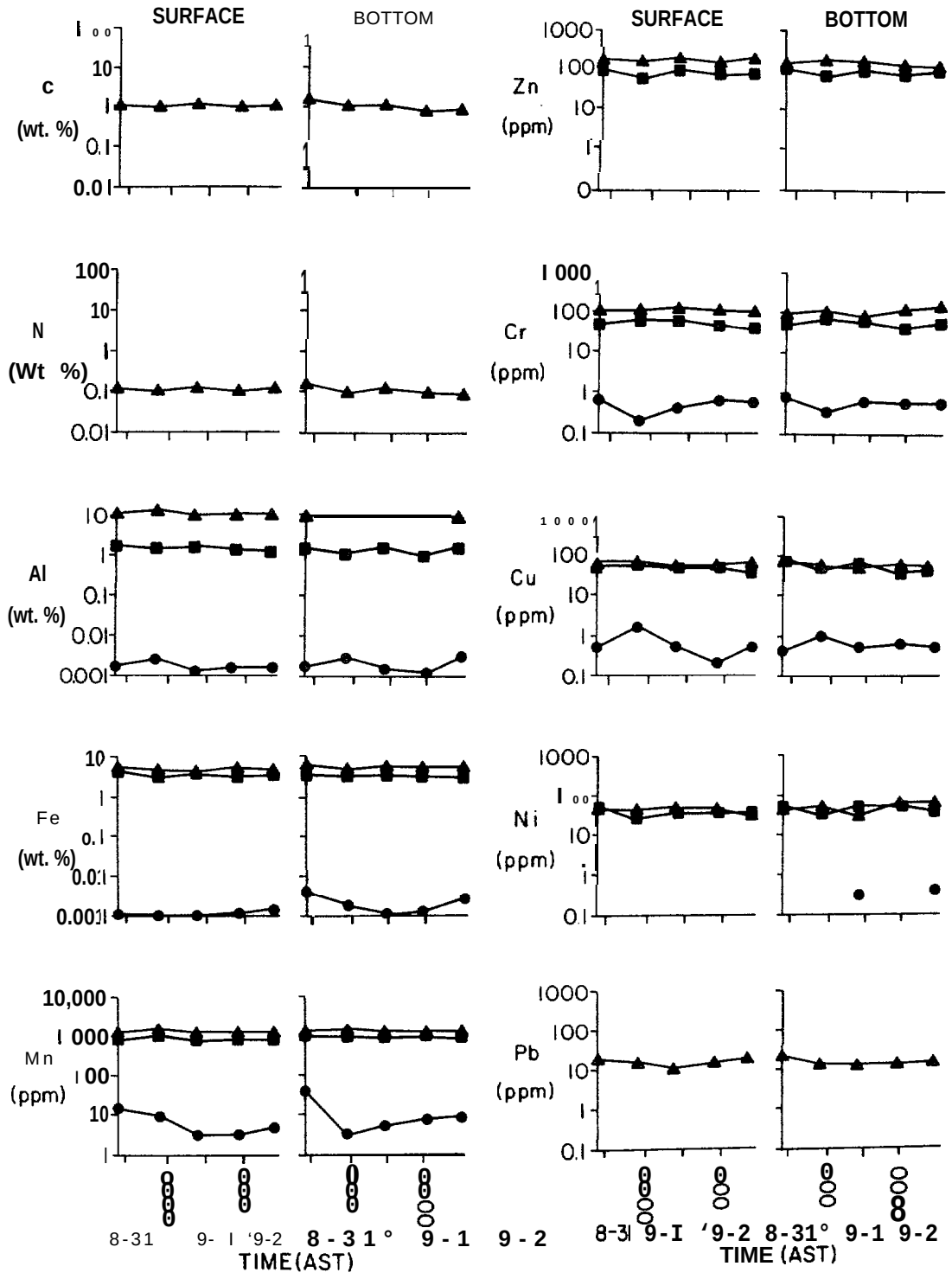

Figure 30. Temporal variations of major and trace elements in suspended matter (total concentration [▲], weak acid extractable [■], and peroxide extractable [●] from station CB-10 in lower Cook Inlet.) Samples were collected 31 August and 1-2 September 1978).

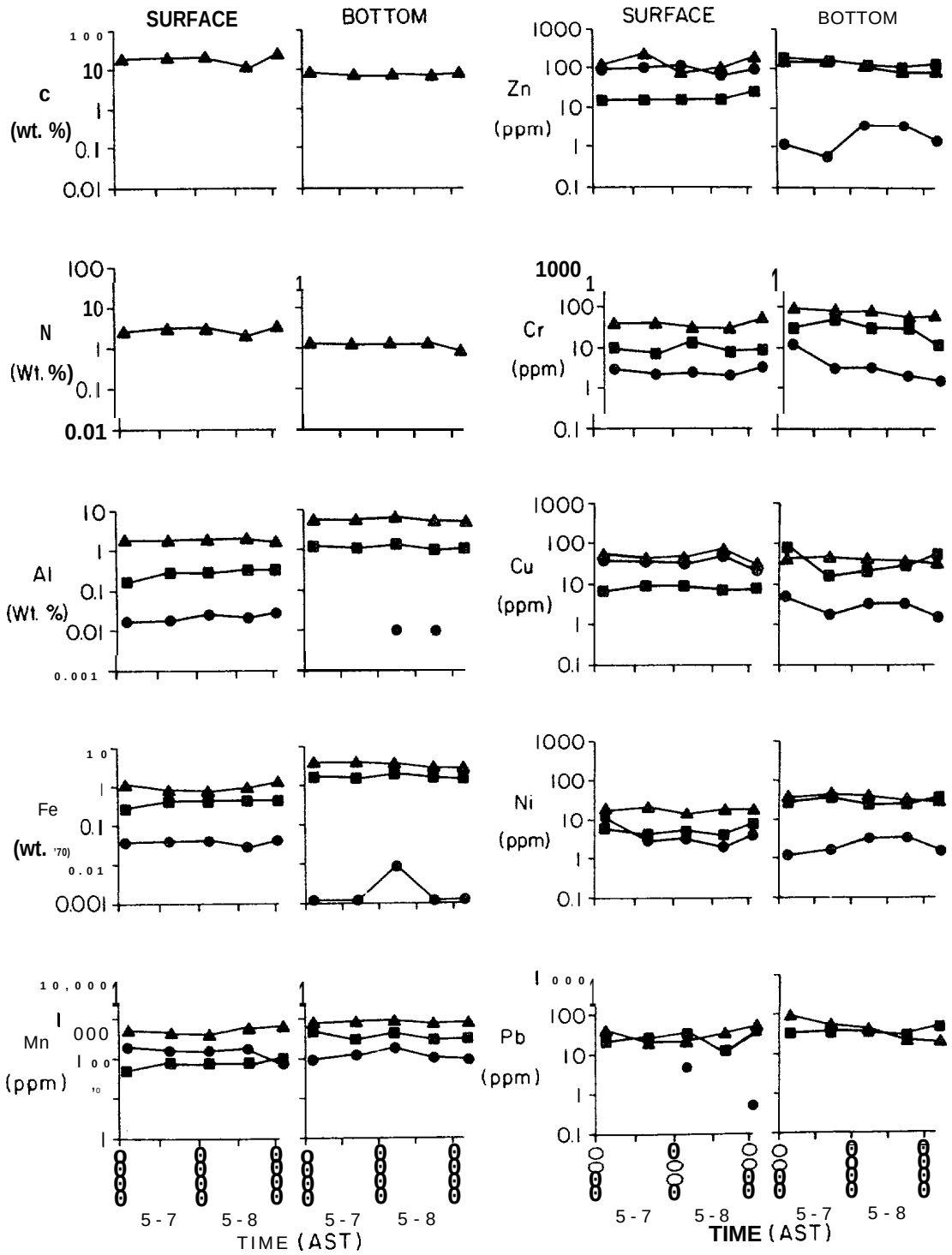

Figure 31. Temporal variations of major and trace elements in suspended matter (total concentration [▲], weak acid extractable [■], and peroxide extractable [●] from station CB-7 in lower Cook Inlet.) Samples were collected 7-9 May 1978.

TABLE 11. Elemental composition and phase association of trace metals in suspended particulate matter from the Kalgin Island Region. Values are the average of samples throughout the time series. Errors are ±1 σ.

	KALGIN ISLAND REGION											
	Surface (CB-9)			Bottom (CB-9)			Surface (CB-1O)			Bottom (CB-1O)		
	Elemental Composition	Peroxide Extractable	Weak Acid xtractable	Elemental Composition	Peroxide Extractable	Weak Acid xtractable	Elemental Composition	Peroxide Extractable	Weak Acid extractable	Elemental Composition	Peroxide Extractable	Weak Acid xtractable
C(wt%)	0.95 ± 0.09			0.89 ± 0.09			1.1 ± 0.1			1.1 ± 0.3		
N(wt%)	0.098 ± 0.014			0.090 ± 0.014			0.11 ± 0.01			0.11 ± 0.03		
Si(wt%)	25.8 ± 1.5			24.7 ± 1.6			25.2 ± 1.0			25.5 ± 2.4		
Al(wt%)	10.4 ± 0.7	0.0038 ± 0.0014	1.04 ± 0.08	10.1 ± 1.5	0.0026 ± 0.0008	0.95 ± 0.15	9.9 ± 1.0	0.0015 ± 0.0002	1.32 ± 0.38	9.0 ± 0.7	0.0021 ± 0.0008	1.26 ± 0.28
Fe(wt%)	5.1 ± 0.5	0.0020 ± 0.0010	3.2 ± 0.5	4.8 ± 0.2	0.0020 ± 0.0012	3.2 ± 0.2	5.3 ± 0.5	0.0010 ± 0.0002	3.3 ± 0.1	5.4 ± 0.8	0.0017 ± 0.0013	3.3 ± 0.6
Mn(ppm)	1310 ± 20	6.3 ± 2.8	1000 ± 180	1300 ± 80	7.3 ± 3.2	940 ± 90	1280 ± 100	8.3 ± 5.9	1060 ± 100	1260 ± 70	6.0 ± 2.2	1030 ± 30
Zn(ppm)	158 ± 9	ND	72 ± 11	151 ± 12	ND	67 ± 7	158 ± 18	ND	86 ± 16	146 ± 18	ND	83 ± 13
Cr(ppm)	108 ± 7	0.5 ± 0.1	55 ± 12	112 ± 12	0.5 ± 0.1	51 ± 5	113 ± 7	0.5 ± 0.2	48 ± *20*	110 ± *27*	0.6 ± *0.2*	47 ± *17*
Cu (ppm)	58 ± 3	1.00 ± 0.13	43 ± 4	55 ± 6	0.80 ± 0.14	36 ± 7	60 ± 6	0.67 ± 0.50	49 ± 15	60 ± 11	0.61 ± 0.24	47 ± 7
Ni (ppm)	46 ± 10	0.25* ± 0.05	38 ± 6	48 ± 6	ND	46 ± 10	45 ± 7	ND	44 ± 9	49 ± 15	0.35* ± 0.05	49 ± 6
Pb(ppm)	23 ± 4	ND	No	20 ± 2	ND	ND	16 ± 4	ND	ND	14 ± 4	ND	ND

ND - Not Detected (< 0.2 ppm for Ni, 0.5 ppm Zn and 1.0 ppm Pb)

* - Three of five samples had nondetectable values. The mean and error are for the two samples with detectable values.

TABLE 12. Elemental composition and phase association of trace metals in suspended matter from Kamishak and Kachemak Bays. Elemental composition values for Kamishak are the averages of duplicate analysis of a single sample. Values for Kachemak Bay are the average of samples throughout the time series. Errors are ±1 u.

	KAMISHAK BAY			KACHEMAK BAY					
	Surface (CB-1)			Surface (CB-7)			Bottom (CB-7)		
	Elemental Composition	Peroxide Extractable	Weak Acid Extractable	Elemental Composition	Peroxide Extractable	Weak Acid Extractable	Elemental Composition	Peroxide Extractable	Weak Acid Extractable
C(wt%)	3.93			19.3 ± 5.6			7.65 ± 0.5		
N(wt%)	0.50			2.9 ± 0.6			1.29 ±0.03		
Si(wt%)	18.9 ± 0.2			18.7 ± 3.7			24.6 ± 2.9		
AL(wt%)	9.3 ± 1.1	0.0035	2.1	2.2 ± 0.4	0.022 ±0. 004	0.29 ± 0.26	5.2 ± 0.5	0.0009 ±0. 0005	1.12 ± 0.13
Fe(wt%)	4.5 ± 0.1	0.022	3.5	1.0 ± 0.3	0.038 ±0. 004	0.44 ± 0.08	3.4 ± 0.4	0.0027 ±0. 0033	1.78 ± 0.19
Mn(ppm)	1110 ± 30	21	882	539 + 86	264 ± 77	81 ± 15	887 , ± 81	124 ± 39	338 ± 89
Zn(ppm)	210 ± 20	0.8	140	159 ± 72	106 ± 20	28 + 7	162 ± 62	2.6 ± 2.0	155 ± 38
Cr(ppm)	158 ± 4	2.1	55	39 ± 12	2.5 ± 0.6	10 ± 2	83 ± 13	2.9 ± 0.6	33 + 14
Cu(ppm)	146 ± 6	14	134	43 ± 12	35 ± 13	8 + 1	39 ± 6	3.3 ± 1.5	42 ± 27
Ni(ppm)	60 ± 2	2.5	37	17 + 2	5 ± 4	17 + 2	37 ± 5	2.2 ± 1.0	34 ± 7
Pb(ppm)	66 ± 3	ND	63	32 + 17	ND	26 + 6	45 ± 29	ND	38 ± 8

ND - Not Detected (< 1.0 ppm for Pb)

case of Cu, Zn and Mn, a major fraction of these elements were present in the organic phase (81%, 66%, and 49%, respectively). The near bottom suspended samples contained 50% aluminosilicates and only 14% organic matter. This influx of inorganic material was probably a result of resuspension of bottom sediments. As expected, the trace metal content in the weak-acid extractable phase increased relative to the surface, consistent with the increased amount of oxyhydroxides associated with the aluminosilicates. The decrease in organic matter content of the near-bottom sample resulted in a smaller portion of the trace metals being present in the peroxide extractable phase.

6.2.5 Elemental Composition of Particulate Matter Collected from Sediment Traps

After the sediment trap particulate were collected and dried for gravimetric measurement, the samples collected at ST-1, ST-2, and CB-7 were analyzed for total elemental composition and phase associations according to section 5. The results of these analyses are listed in table 13.

There are significant regional differences in the major elemental composition of the sediment trap particulate which can be related to the source suspended particulate matter. The Al content of the sediment trap particulate at ST-1 in Kamishak Bay was higher than that at CB-7 in Kachemak Bay. The Al content of the suspended particulate material also follows this relationship (Feely and Massoth, in press), indicating the dominance of aluminosilicates on the western side of lower Cook Inlet. Several trace metals (Fe, Cr, and Ni) which are associated with aluminosilicates in the suspended particulate matter also had significantly greater concentrations in the sediment trap particulate of Kamishak Bay relative to those of Kachemak Bay.

In contrast, Kachemak Bay sediment trap samples contained three times as much organic C as those of Kamishak Bay, indicating a similar relationship in the organic C flux (0.95 g m^{-2} d^{-1} at CB-7 as compared to 0.32 g m^{-2} d^{-1} at ST-l). As a result of high primary productivity in Kachemak Bay (Larrance et al., 1977), the suspended particulate matter contained about 20% organic C and had a C/N ratio of 6.7 characteristic of a marine origin. The sediment trap particulate also had a C/N characteristic of a marine origin, indicating that the surface suspended matter was a major source of organic C to the sediment trap. The lower primary productivity in Kamishak Bay resulted in a significant portion of the organic C flux being terrestrial in origin as indicated by a C/N ratio midway between marine and terrestrial organic matter. Therefore, it appears that there is a definite relationship between production of organic matter in the water column and the amount and type of organic matter settling to the bottom, thus providing a food source for filter-feeding benthic organisms.

The trace metal data for the sediment trap particulate showed similar associations with the oxyhydroxide phase in all three sediment trap stations. For instance, the portion of Cr present in the weak-acid extractable phase ranged from 49% - 56% of total Cr for the samples from the three stations, while 100% of the Ni was present in this phase. These trace metal associations were similar to those found in the suspended matter, emphasizing the importance of the oxyhydroxide phase in transporting metals through the water column.

The trace metal data in the peroxide extractable phase show regional differences consistent with the organic fluxes. With the exception of Cr, the trace metals present in the peroxide extractable phase follow the order: CB-7 > ST-1 > ST-2. The organic fraction of Kachemak Bay sediment trap partic-

ulates contained 5.3% and 10.9% of the total Mn and Cu, respectively, present in the whole sample. The coupling between biological accumulation of trace metals in the water column and the flux of organically bound trace metals is demonstrated by the fact that a major portion of both Cu and Mn were also present in the organic fraction of the surface suspended matter (see section 6.2.3). This coupling may be a major mechanism for transporting these trace metals to the benthic community.

The significance of these results is evident when one considers recent studies of the availability of sediment bound trace elements to organisms. Luoma and Bryan (1978) studied the distribution of Pb and Fe in the soft tissues of the deposit feeding bivalve Scorbicularia plana and in the underlying sediments from 20 estuaries in southern and western England and northwest France. It was found that the Pb concentrations in the bivalves directly" correlated with the Pb/Fe ratio in the sediment. The authors concluded that the Fe concentration in the sediments was influencing the availability of Pb to the bivalves. To be more specific, they suggested that the availability of Pb to the bivalves may be a function of the partitioning of Pb between organically bound Pb and Fe oxide-bound Pb in the sediments, with the organically bound Pb being more biologically available. Similarly, Eaganhouse and others (1976; 1978) found enrichments of Hg in tissues of the intertidal mussel Mytilus californianus in sediments that contained high concentrations of organically bound Hg. Here again, the implication is that organically bound trace elements are more available to organisms than trace elements that are bound to some other less available phase in the sediments. In lower Cook Inlet organically bound trace elements predominate only in Kachemak Bay where primary production is higher than any other region in the inlet. It is also the region

TABLE 13. **Elemental composition and phase association of trace metals in sediment trap particulate at ST-1, ST-2 and CB-7. Values for ST-1 and ST-2 are the average of triplicate analysis of a single sample from a long-term deployment. Values for CB-7 are the average of four samples from short-term deployment. Errors are ±1 u.**

	ST-1 (32111)			ST-2 (75[11)			CB-7 (60m)		
	Elemental Composition	Peroxide Extractable	Weak Acid Extractable	Elemental Composition	Peroxide Extractable	Weak Acid Extractable	Elemental Composition	Peroxide Extractable	Weak Acid Extractable
C(wt%)	0.87 ± 0.02			0.84 ± 0.40			2.8 ± 0.4		
N(wt%)	0.09 ± 0.01			0.09 ± 0.05			0.35 ± 0.05		
Si(wt%)	21.8 ± 1.0			26.5 ± 1.0			22.5 ± 3.2		
Al(wt%)	9.4 ± 0.9	0.0011 ±0.0004	3.0 ± 0.3	7.8 ± 1.0	0.0004 ±0.0004	1.2 ± 0.6	6.5 ± 0.5	0.0035 ±0.0017	1.16 ± 0.10
Fe(wt%)	4.6 ± 0.2	0.0010 ±0.0004	3.22 ±0.05	3.4 ± 0.1	0.0004 ±0.0002	2.1 ± 0.3	3.8 ± 0.9	0.0022 ±0.0007	1.2 ± 0.2
Mn (ppm)	880 ± 80	3 ± 3	426 ± 27	660 ± 35	0.6 ± 0.1	265 ± 45	915 ± 170	48 ± 29	570 ± 140
Zn(ppm)	142 ± 6	ND	118 ± 5	106 ± 20	ND	74 ± 2	215 ± 120	0.6 ± 0.3	160 ± 86
Cr(ppm)	82 ± 2	0.3 ± 0.1	40 ± 2	55 ± 6	1.5 ± 0.5	31 ± 2	63 ± 8	2.4 ± 0.3	35 ± 3
Cu(ppm)	29 ± 2	0.12 ± 0.01	23 ± 2	18 ± 2	0.04 ± 0.01	13 ± "3	43 ± 3	4.7 ± 0.8	36 ± 7
Ni (ppm)	51 ± 14	ND	51 ± 1	30 ± 7	ND	30 ± 6	34 ± 2	1.3 ± 0.1	37 ± 6
Pb(ppm)	15 ± 2	ND	ND	10 ± 2	ND	ND	13 ± 6	ND	1.1 ± 0.5

ND - Not Detected (< 0.2 ppm for Ni and Zn and 1.0 ppm for Pb)

where water circulation is the least dynamic. Therefore, it is possible to speculate that anthropogenic inputs of dissolved trace metals resulting from development activities would have a more profound impact on biological communities in Kachemak Bay than other regions in lower Cook Inlet because of their apparent incorporation into biologically available organic matter.

6.3 Southeastern Bering Shelf

6.3.1 Particulate Matter Distribution

Figures 32 thru 35 show the distribution of suspended matter at the surface and 5 meters above the bottom for the fall and summer cruises in the southeastern Bering Sea Shelf (RP-4-Di-76B-III, 12 September - 5 October 1975 and RP-4-MW-76B-VIII, 24 June - 9 July 1976). As shown in figures 32 and 34, the surface particulate matter distributions are dominated by the discharge of suspended material from the northern rivers. Large plumes of suspended matter extend to the southwest from Kuskokwim Bay and the region east of Cape Newenham. Similar suspended matter distributions were found by Sharma et al. (1974) from samples collected during June-July 1973. The authors suggested that suspended material originating from the Kvichak and Nushagak Rivers moves generally to the west until it reaches Cape Newenham where it combines with a portion of the material discharged from the Kuskokwim River and is deflected to the southwest. Chemical analysis of the particulate matter suggests that the material is essentially of terrestrial origin (> 76% inorganic).

Along the Alaska Peninsula surface suspended matter concentrations decrease rapidly away from the coast. This is due to rapid mixing of the highly turbid Shelf water with the relatively clear Pacific Ocean water which originates from the passes west of the Alaska Peninsula and is deflected to the northeast along the coast of the Alaska Peninsula.

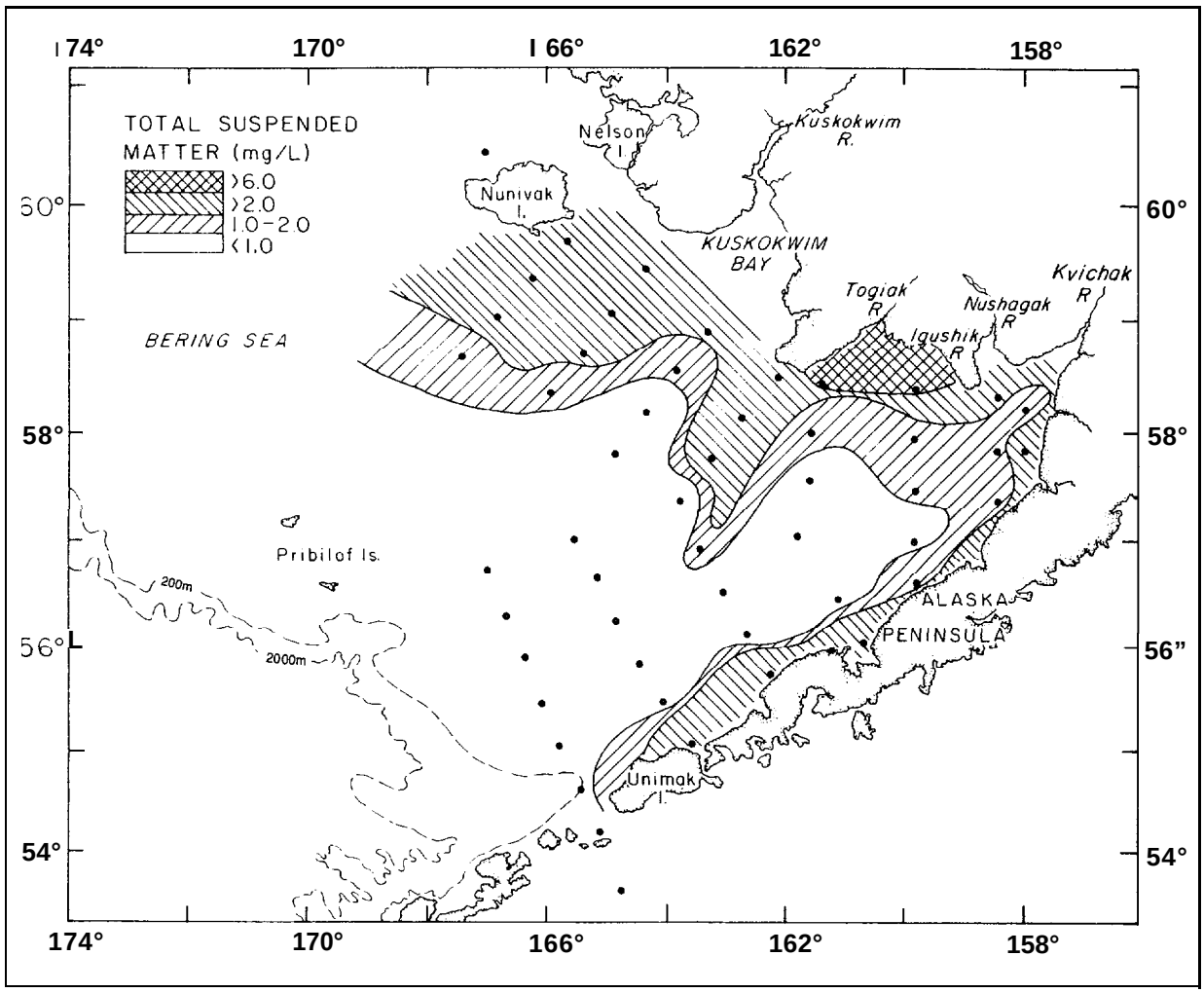

Figure 32. **Distribution of total suspended matter at the surface in the southeastern Bering Shelf (Cruise RP–4-Di-75B-III, 12 September - 5 October 1975).**

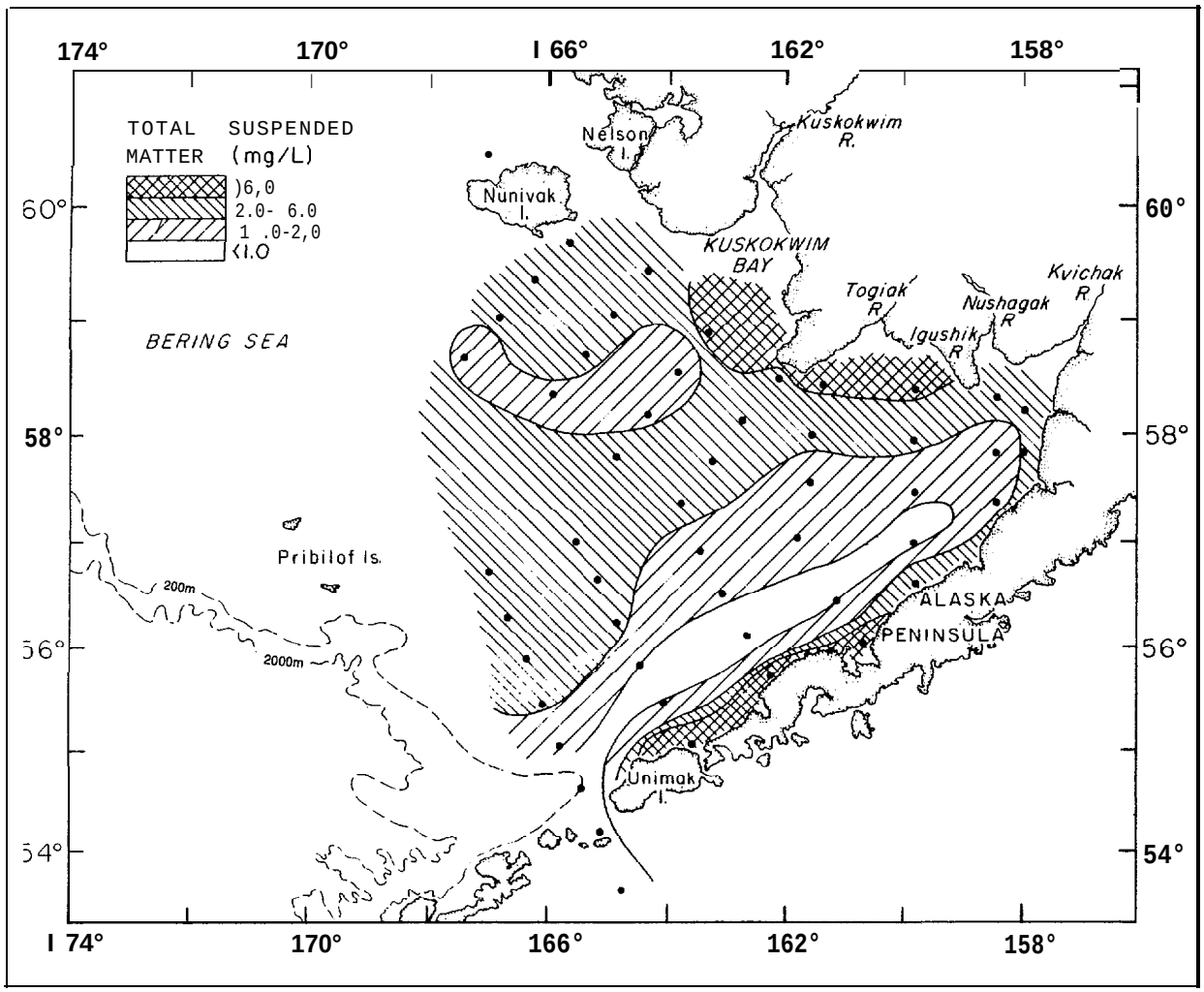

Figure 33. Distribution of total suspended matter 5 meters above the bottom in the southeastern Bering Shelf (Cruise RP-4-Di-75B-III, 12 September - 5 October 1975).

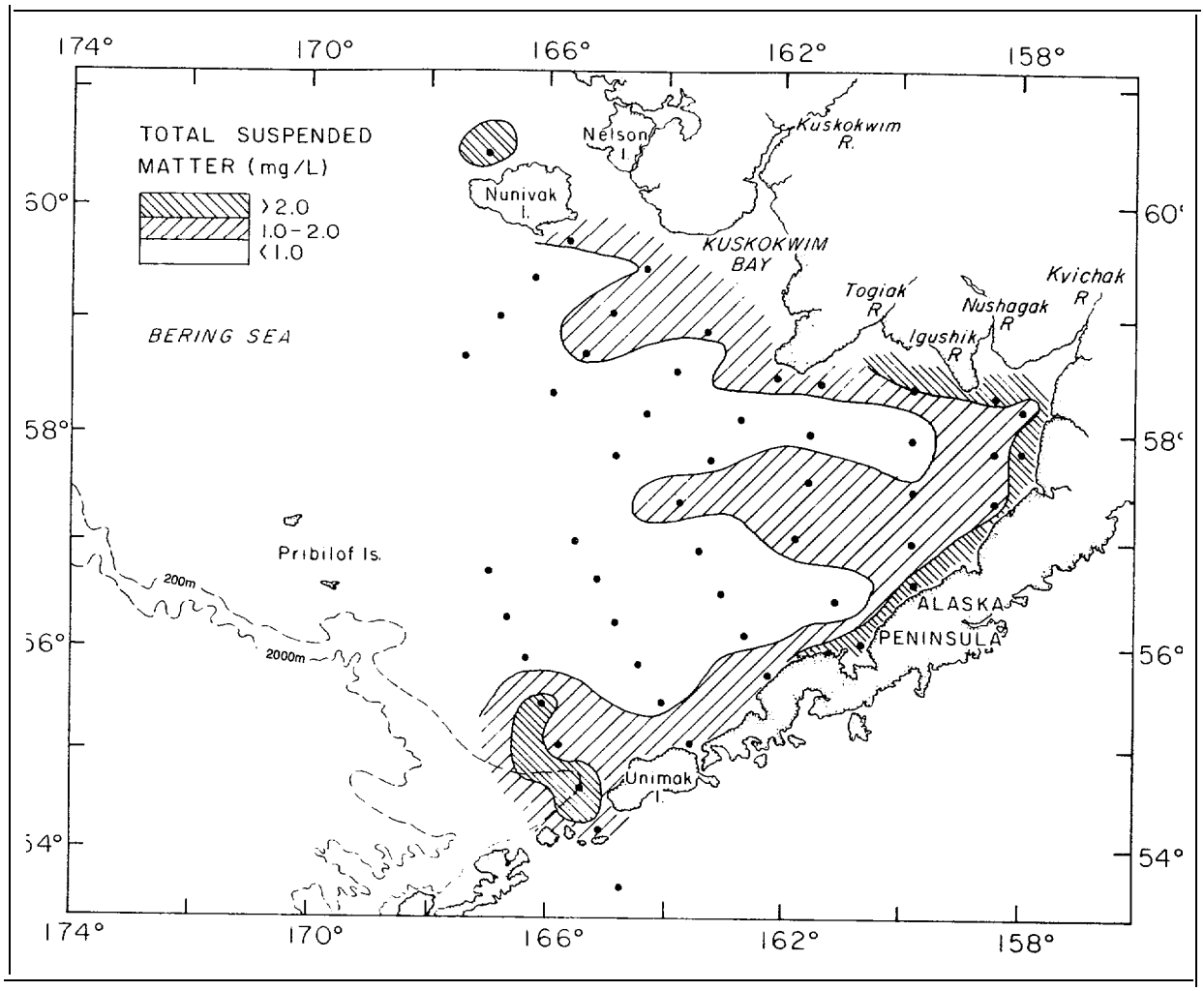

Figure 34. Distribution of total suspended matter at the surface in the southeastern Bering Shelf (Cruise RP-4-MW-76B-VII, 24 June - 9 July 1976).

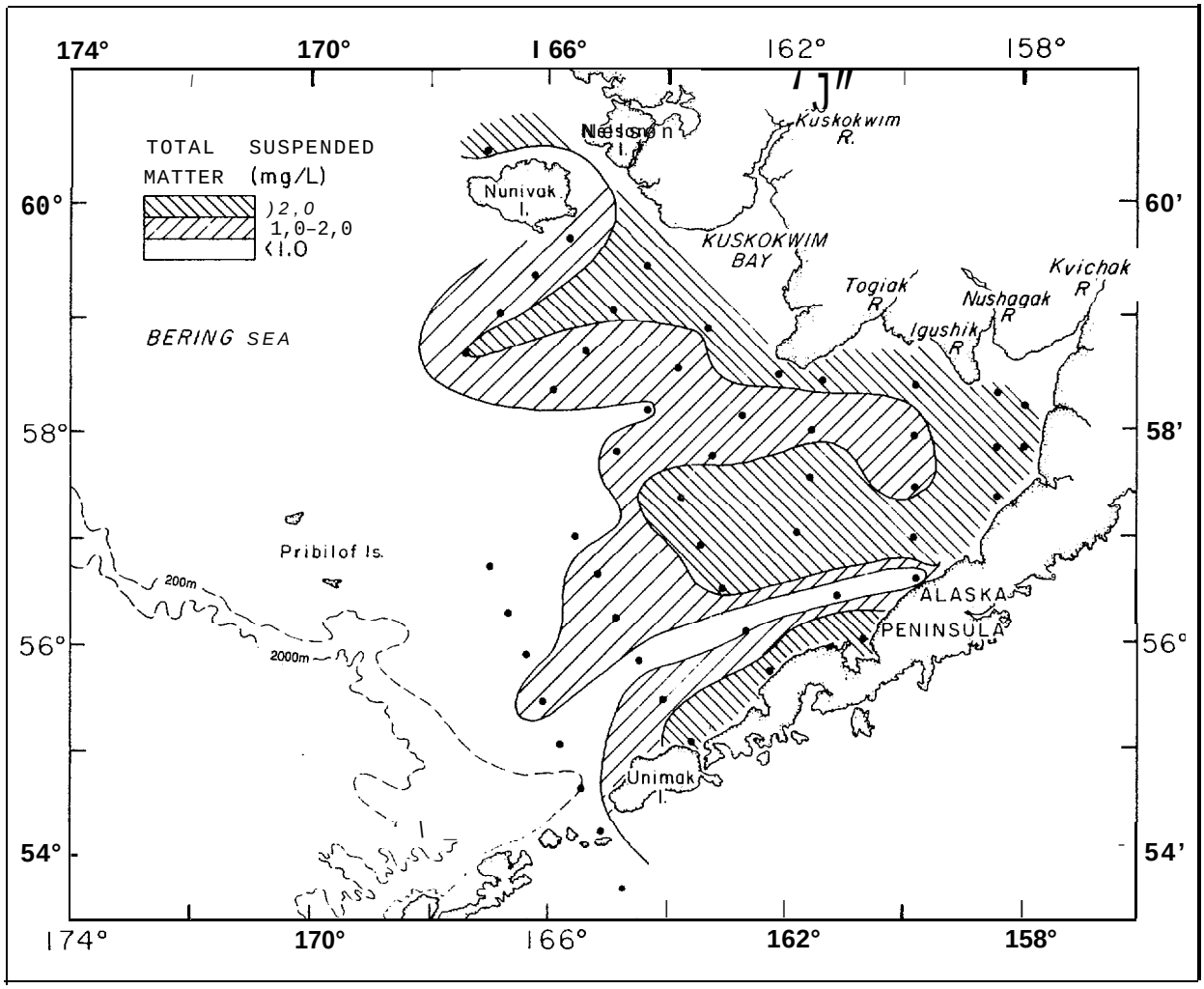

Figure 35. Distribution of total suspended matter 5 meters above the bottom in the southeastern Bering Shelf (Cruise RP-4-Mw-76B-VII, 24 June - 9 July 1976).

At the time of the summer cruise, plumes of turbid water were observed north of Unimak Island and in the region west of the northern end of the Alaska Peninsula which were not observed during the fall cruise (figure 34). These plumes might be attributed to the large seasonal variations in primary productivity which are characteristic of this region. Sharma et al. (1974) observed turbid plumes in the region northwest of Unimak Pass which they attributed to similar processes.

Near the bottom, suspended matter concentrations are high (> 1.0 mg/L) throughout most of the study region, indicating possible resuspension of bottom sediments. Figures 36 and 37 show vertical cross-sections of the distribution of particulate matter from Kuskokwim Bay to Unimak Island for both cruises. The figures show increasing suspended matter gradients near the bottom which are attributed to resuspension and redistribution of bottom sediments. Since Bristol Bay is a relatively shallow embayment, it is possible that waves and tides play a major role in the redistribution of sediments. The suspended matter concentrations near the bottom were 2-3 times higher in the fall. This may be due to the increased effect of storms which occur more regularly during the fall months.

6.3.2 Elemental Chemistry of the Particulate Matter

Tables 14 and 15, respectively, summarize the data on the elemental composition of the particulate matter from the major rivers discharging into Bristol Bay and from 42 stations on the Shelf. For convenience, the surface data in table 15 have been arranged into three groups. Group I contains all the northern stations in which the sum of the major inorganic element concentrations (expressed as oxides) is greater than 60 percent of the total weight of material on the filter. Group II contains all the southern stations

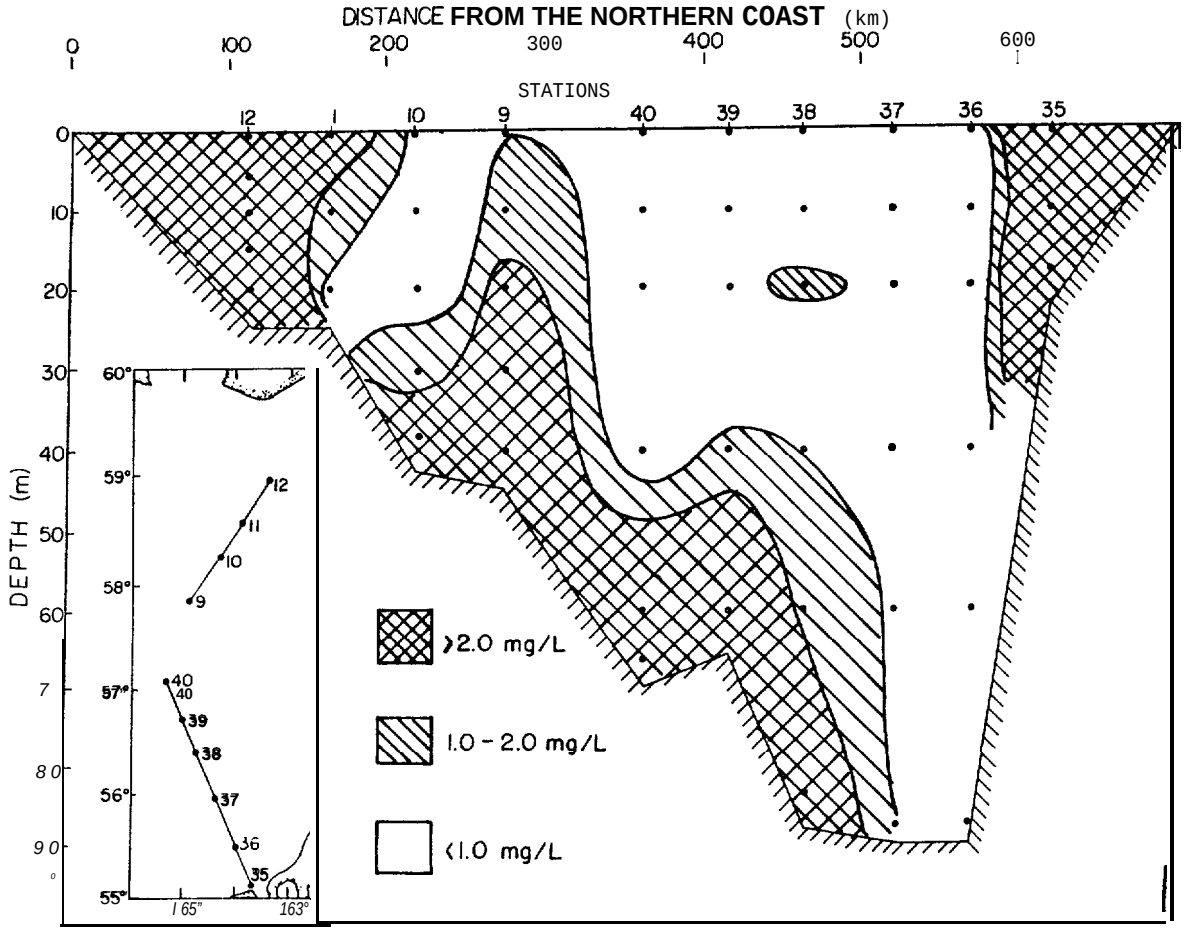

Figure 36. Vertical cross-section of the distribution of total suspended matter for stations 9 thru 12 and 35 thru 40 in the southeastern Bering Shelf (Cruise RP-4-Di-75B-III, 12 September - 5 October 1975).

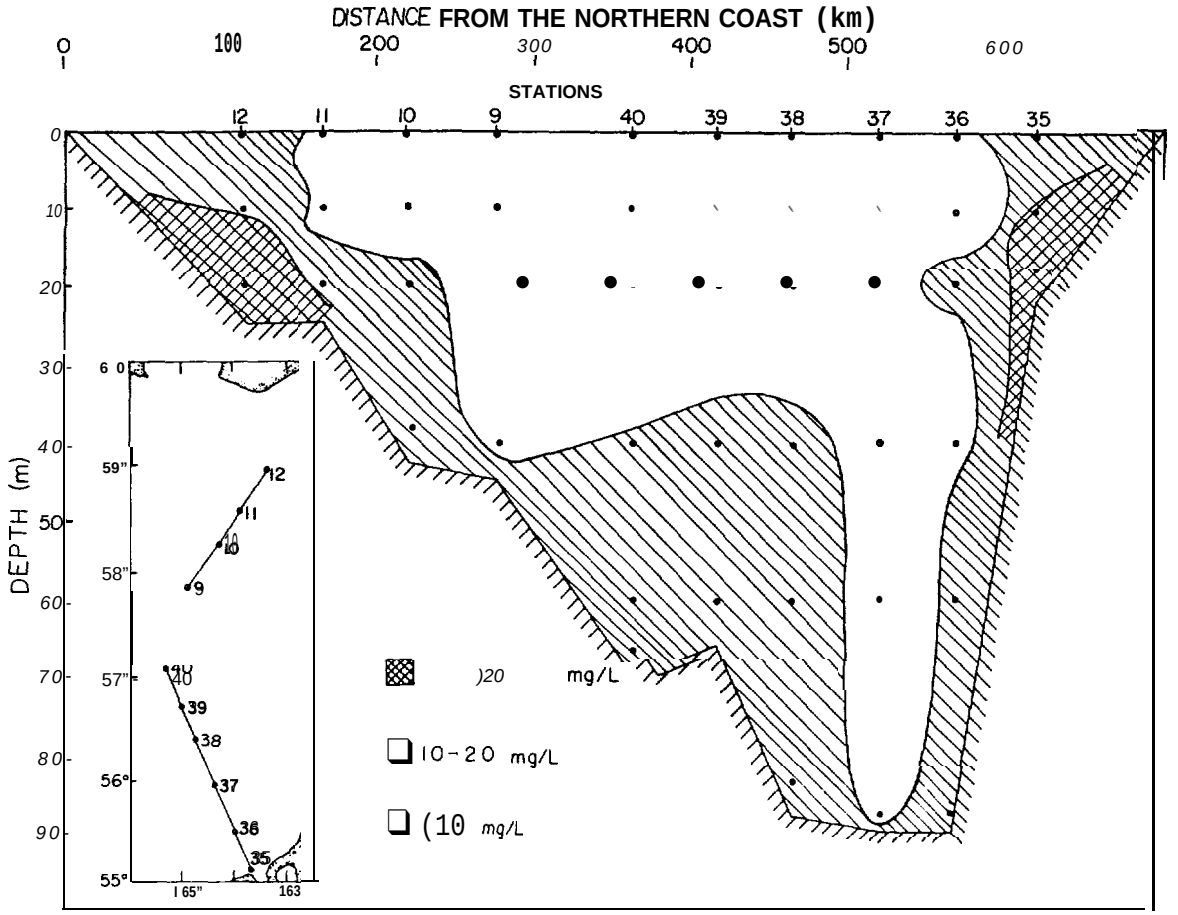

Figure 37. Vertical cross-section of the distribution of total suspended matter for stations 9 thru 12 and 35 thru 40 in the southeastern Bering Shelf (Cruise RP-4-MW-76B-VIII, 24 June - 9 July 1976).

in which the sum of the major inorganic element concentrations is also greater than 60 percent of the total weight. Group III contains all the stations in between in which the sum is less than 60 percent of the total suspended load.

As shown in table 15, Groups I and II are very similar and appear to be dominated by the supply of terrigeneous material from the Kuskokwim, Nushagak, and Kvichak Rivers to the north (for Group I) and the coastal streams and lagoons to the south (for Group II). Several authors have suggested that since Mg, Al, K, and Ti are almost exclusively associated with aluminosilicate minerals, the presence of these elements in particulate matter is indicative of terrestrial input (Spencer and Sachs, 1970; Price and Calvert, 1973; and Feely, 1975). The high concentrations of these elements in the samples from Groups I and II indicate that aluminosilicate minerals are the most dominant solid phase in the particulate matter. The data from table 15 show that for Groups I and II approximately 35-60 percent of the particulate matter is aluminosilicate material. In contrast, the particulate matter samples from Group 111 only contain about 20 percent aluminosilicate material.

The Group 111 samples are significantly depleted in particulate Mg, Al, Si, K, Ca, Ti, Mn, and Fe and are enriched in Ni, Cu, and Zn. The trace element enrichments are 134, 53, 21 percent, respectively, for Ni, Cu, and Zn. However, considering the large sample variability associated with the low sample loadings, these enrichments may not be significant.

Since the early work of Menzel and Vaccaro (1964), many investigators have used particulate C as a tracer of particulate organic matter in the oceans. Gordon (1970) suggested that a factor of 1.8 be used to estimate concentrations of particulate organic matter from particulate C. Recent investigators have used the C/N ratios in particulate matter to distinguish

TABLE 14

Summary of the elemental composition of particulate matter from the major rivers that discharge into the southeastern Bering Shelf. (Surface samples were obtained with a precleaned 4-L polyethylene bottle extended from a helicopter, 12-21 September 1976.)

Sample Location	No. of Samples	C wt. %	N wt. %	Mg wt. %	Al wt. %	Si wt. %	K Wt. %	Ca wt. %	Ti wt. %	Cr ppm	Mn ppm	Fe wt. %	Ni ppm	Cu ppm	Zn ppm
Kuskokwim River	9	2.96 ±2.63	0.38 ±0.42	2.13 ±0.39	7.77 ±0.98	32.13 ±2.86	1.68 ±0.16	1.59 ±0.07	0.56 ±0.04	105.3 ±14.9	1498 ±105	6.57 ±0.45	69.8 ±4.8	77.6 ±7.3	281.4 ±34.2
Kvichak	6	2.66 ±0.15	0.23 ±0.15	].24 ±0.44	4.26 ±1.07	26.78 ±10.30	0.81 ±0.16	0.48 ±0.13	0.42 toll	62.2 ±18.3	941 ±53	4.36 ±1.32	36.3 ±10.9	63.3 ±8.7	232.1 ±108.8

TABLE 15

Summary of the elemental composition of the particulate matter samples from the southeastern Bering Shelf (Cruise RP-4-Di-75B-III, 12 September - 6 October 1975)

Sample Description	No. of Samples	C wt. %	N wt. %	Mg wt. %	Al wt. %	Si wt. %	K wt. %	Ca wt. %	Ti wt. %	Cr ppm	Mn ppm	Fe wt. %	Ni ppm	Cu ppm	Zn ppm
Surface (Group I)	**24**	**17.7 ±10.3**	**2.1 ±1.3**	**0.86 ±0.14**	**3.52 ±2.22**	25.85 ±5.28	0.51 ±0.17	1.32 ±0.28	0.24 ±0.06	41.2 ±19.3	893 ±285	2.68 ±0.63	24.1	41.9 ±13.9	210.7 ±88.0
Surface (Group 11)	4	22.9		1.75 ±0.08	6.11 ±1.32	31.74 ±6.40	0.37 ±0.14	2.66 ±0.89	0.28 ±0.07		1377 ±519	3.15 ±0.35		42.4 ±21.8	353.0 ±127.0
Surface (Group III)	11	35.3 ±19.3	4.8 ?2.7			10.89 ±6.73	0.26 ±0.20	1.14 ±0.50	0.18 ±0.07	60.4 ±32.2	*355 233	1.92 ±0.66	56.5 ±11.7	64.0 ±31.4	256.0 ±215.0
5 m **above** the bottom	42	12.2 ±7.6	1.8 ±1.1	1.45 ±0.66	3.92 ±1.27	29.45 ±6.12	0.53 ±0.17	1.64 ±0.65	0.28 ±0.07	50.0 ±20.9	581 ±304	3.16 ±0.82	30.7 ±17.9	54.2 ±47.7	219.6 ±107.6

between terrestrial and marine sources of organicmatter(Loderand Hood, 1972). The authors found that riverborue organic matter has C/N ratios which range between 15-22. in contrast, ratios for marine organic matter range between 5-15.

The distribution of particulate C and N at the surface in the southeastern Bering Shelf are presented in figures 38 and 39. Generally speaking, the surface distributions follow the same pattern as total suspended matter. High concentrations of particulate C and N are found along the coast with concentration gradients decreasing slowly in a seaward direction from the northern coast and rapidly from the coast of the Alaska Peninsula. A plume of turbid water containing high concentrations of particulate C and N extends to the southwest from Kuskokwim Bay. Apparently, the semipermanent counterclockwise currents which appear to be controlling the distributions of total particulate matter at the surface also control the distribution of particulate C and N.

The C/N ratios in the particulate matter at the surface indicate that the organic matter is primarily of marine origin. Ratios range from 0.7 to 29.4 with a mean 7.2. Although the ratios increase slightly from south to north, studies of the variability of C/N ratios in marine phytoplankton indicate that these small increases are probably not significant (Banse, 1974).

6.4 Norton Sound

6.4.1 Particulate Matter Distribution and Transport

Figures 40 and 41 show the distributions of total suspended matter at the surface and 5 m above the bottom for the July 1979 cruise in Norton Sound. As shown in figure 40, surface particulate matter distributions were dominated by

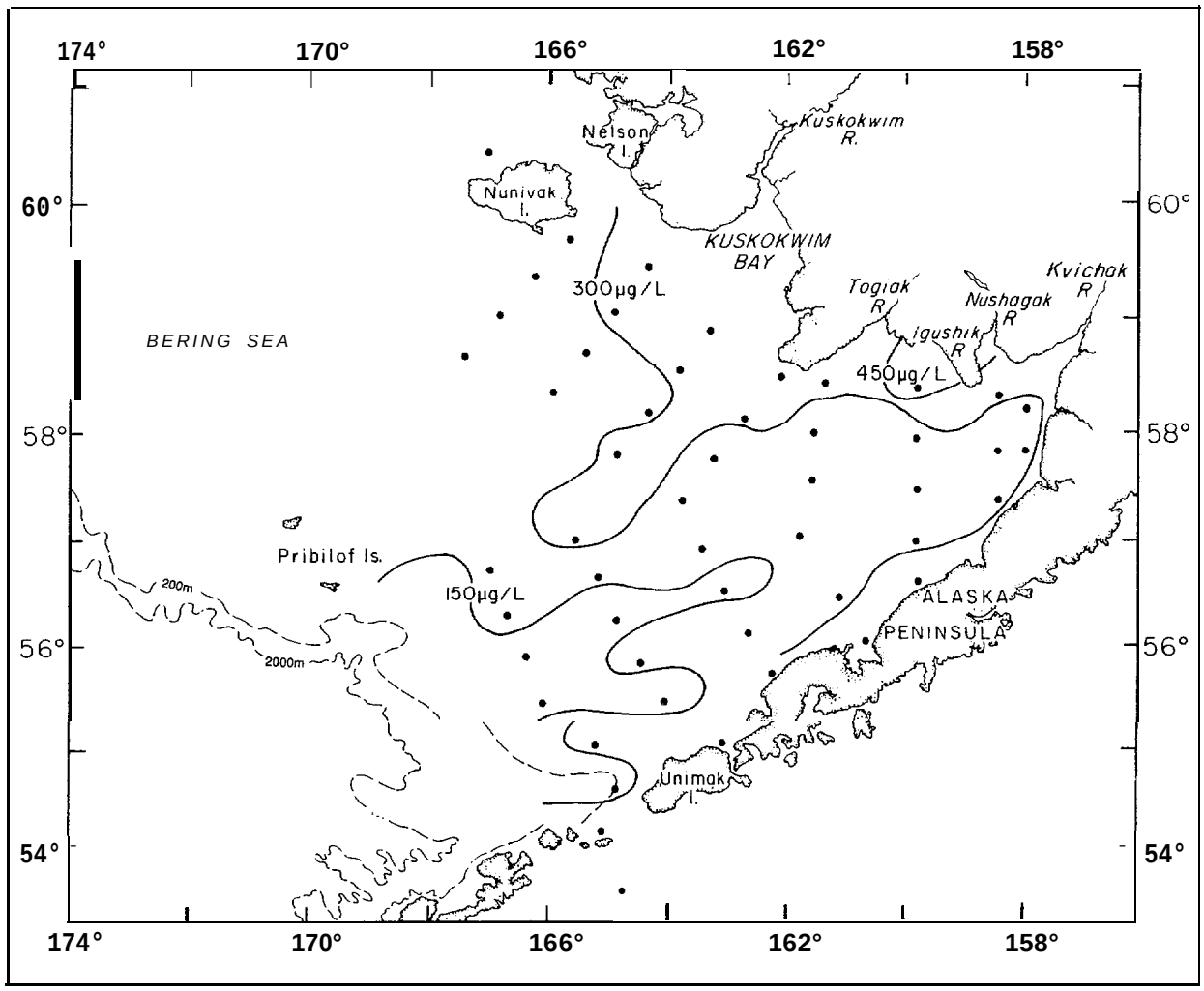

Figure 38. Distribution of total particulate carbon at the surface in the southeastern Bering Shelf (Cruise RP-4-Di-75B-III, 12 September - 5 October 1975).

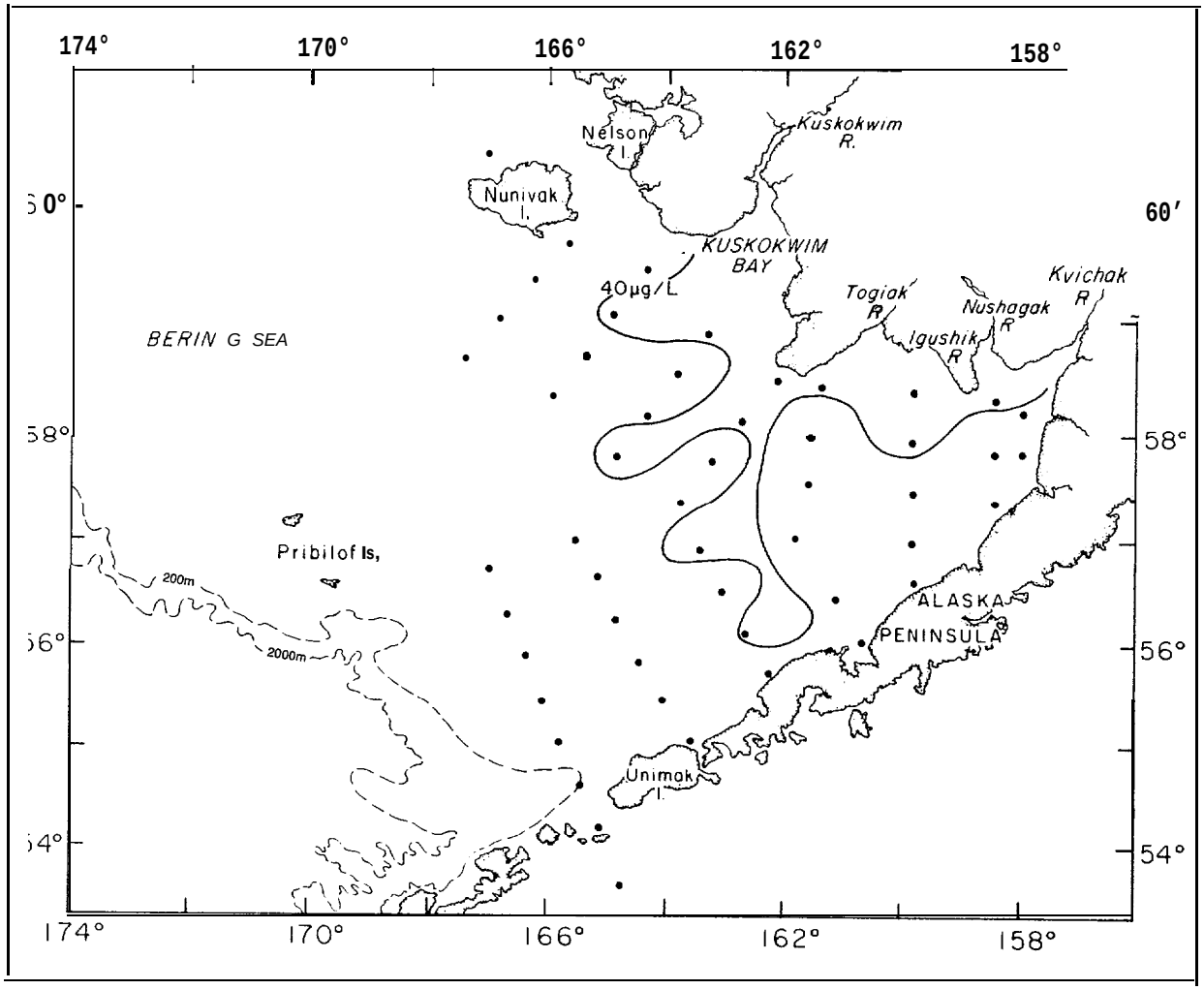

Figure 39. Distribution of total particulate nitrogen at the surface in the southeastern Bering Shelf (Cruise RP-4-Di-75B-III, 12 September - 5 October 1975).

the discharge of sedimentary material from the Yukon River. Surface suspended matter concentrations were highest near the mouth of the Yukon River, where values ranging between 100 and 154 mg/L were observed. The Yukon River plume (as indicated by the 5.0 mg/L isopleth) extended to the north and northeast across the length of the Sound. Another portion of the plume with lesser suspended matter concentrations (1.0-2.7 mg/L) extended north and northwest to a point about 20 km southwest of Cape Rodney. Both portions appear to have originated from the Yukon River and their trajectories tend to follow the general pattern of cyclonic circulation in the Sound (i.e., Yukon River material enters the Sound from the southwest, is transported north and northeast around the inside perimeter of the Sound, and exits the Sound from the northwest) . These data are supported by the salinity and temperature measurements which indicated movements of low-salinity (12-24^{o}/oo), relatively warm (10-11"C) water to the northeast along the coast (Feely et al., 1981). These results are consistent with the general conclusions of Sharma et al. (1974) for suspended matter data obtained in August 1973. They are also consistent with dispersal patterns of the Yukon River plume inferred from LANDSAT satellite photographs (Nelson et al., 1975). For example, figure 42 shows a LANDSAT photograph of the Yukon River plume taken on July 20, 1979, a few days following Cruise RP-4-Di-79A-VI. The plume, which appears lighter in the grey tones than the less turbid water, can be traced as far north as approximately 70 km from the Yukon River Delta and as far east as 50 km from Stuart Island. These features are also consistent with the data of Cacchione and Drake (1979) for surveys made during quiescent periods in September 1976 and July 1977.' Thus, it would appear that the transport processes described above predominate throughout the region, at least during periods of calm weather in the summer.

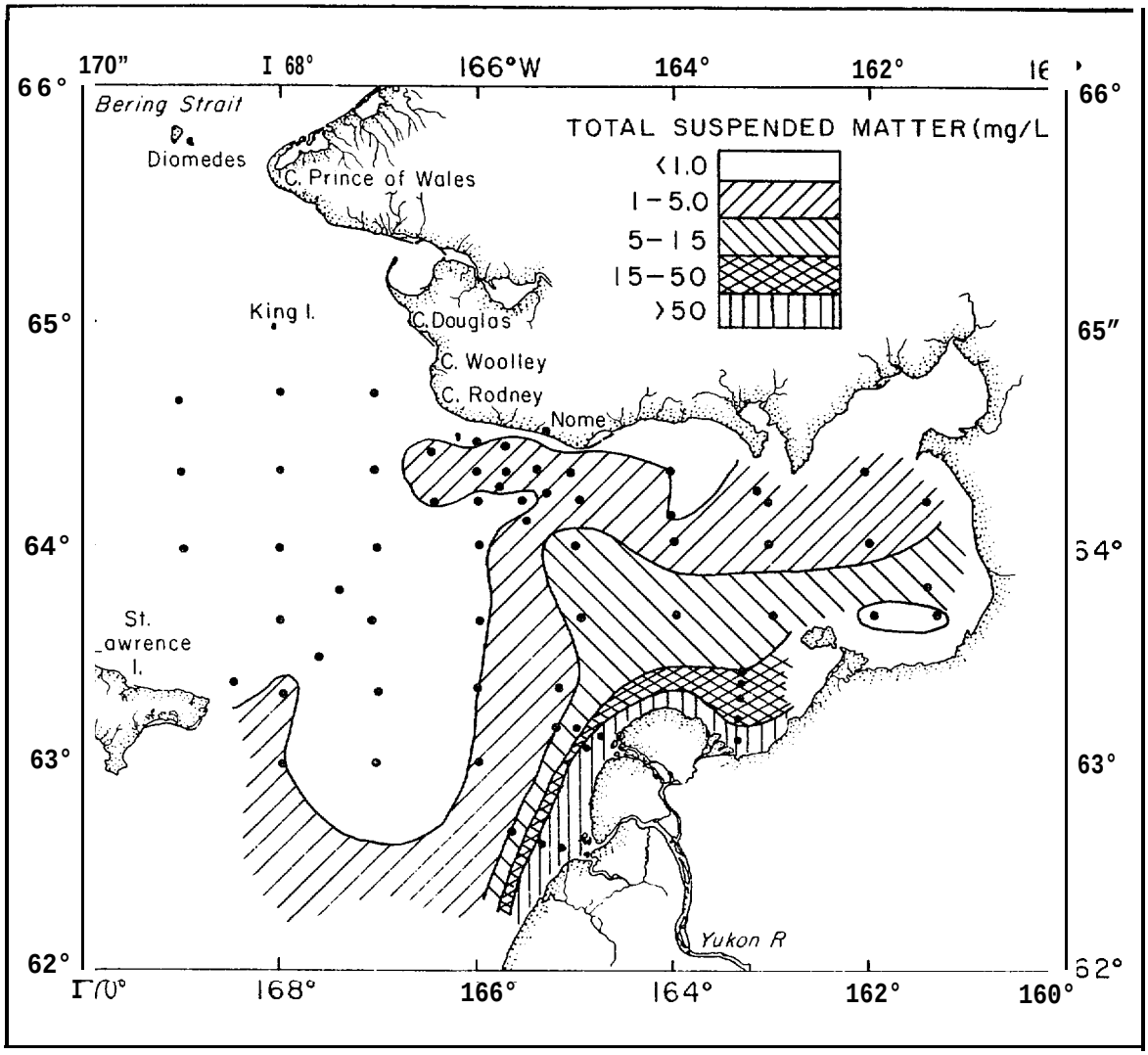

Figure 40. **Distribution of total suspended matter at the surface in Norton** Sound (Cruise RP-4-Di-79A-VI, **7-18 July 1979).**

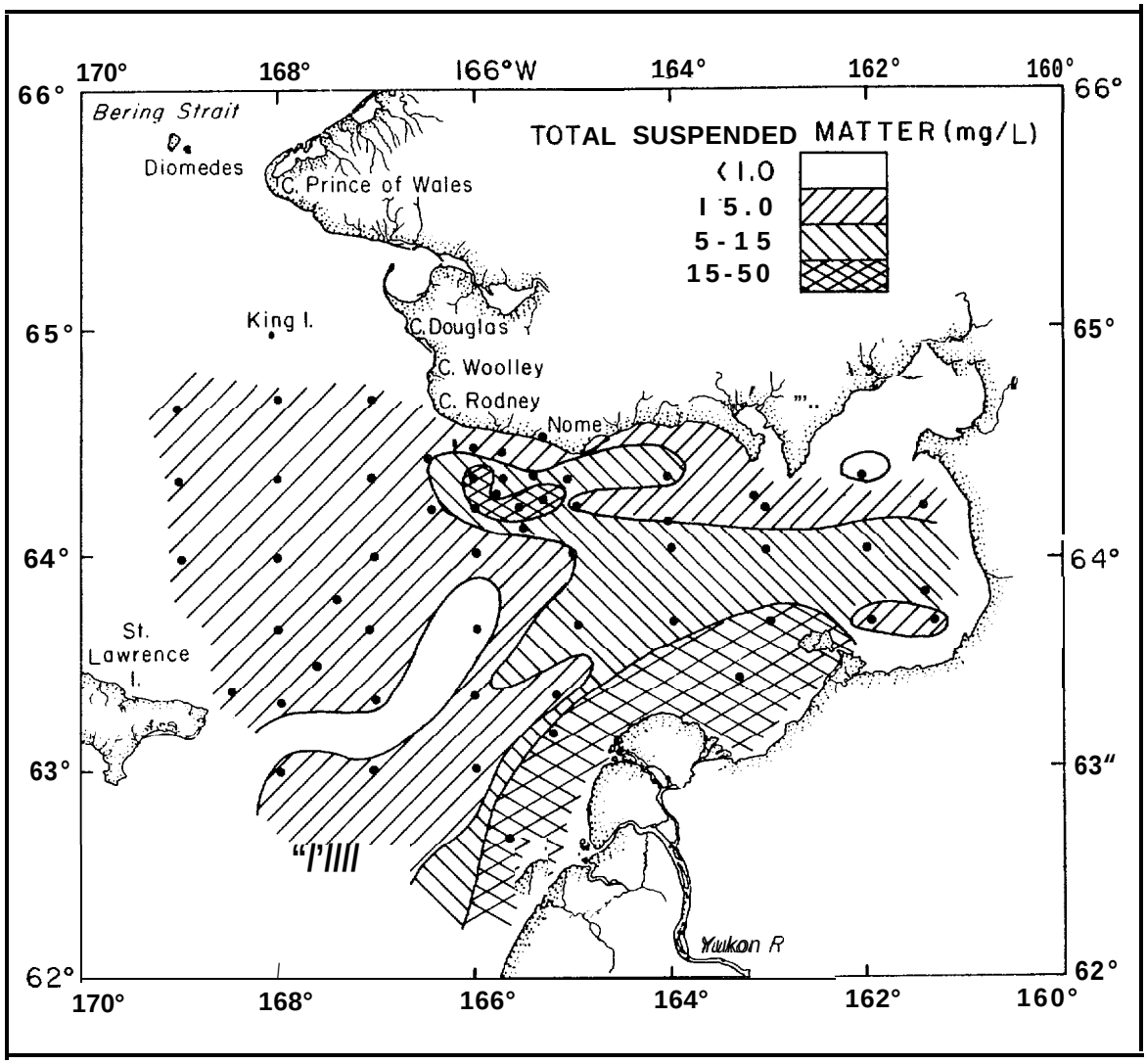

Figure 41. **Distribution of total suspended matter at 5 m above the bottom in Norton Sound (Cruise RP-4-Di-79A-VI, 7-18 July 1979).**

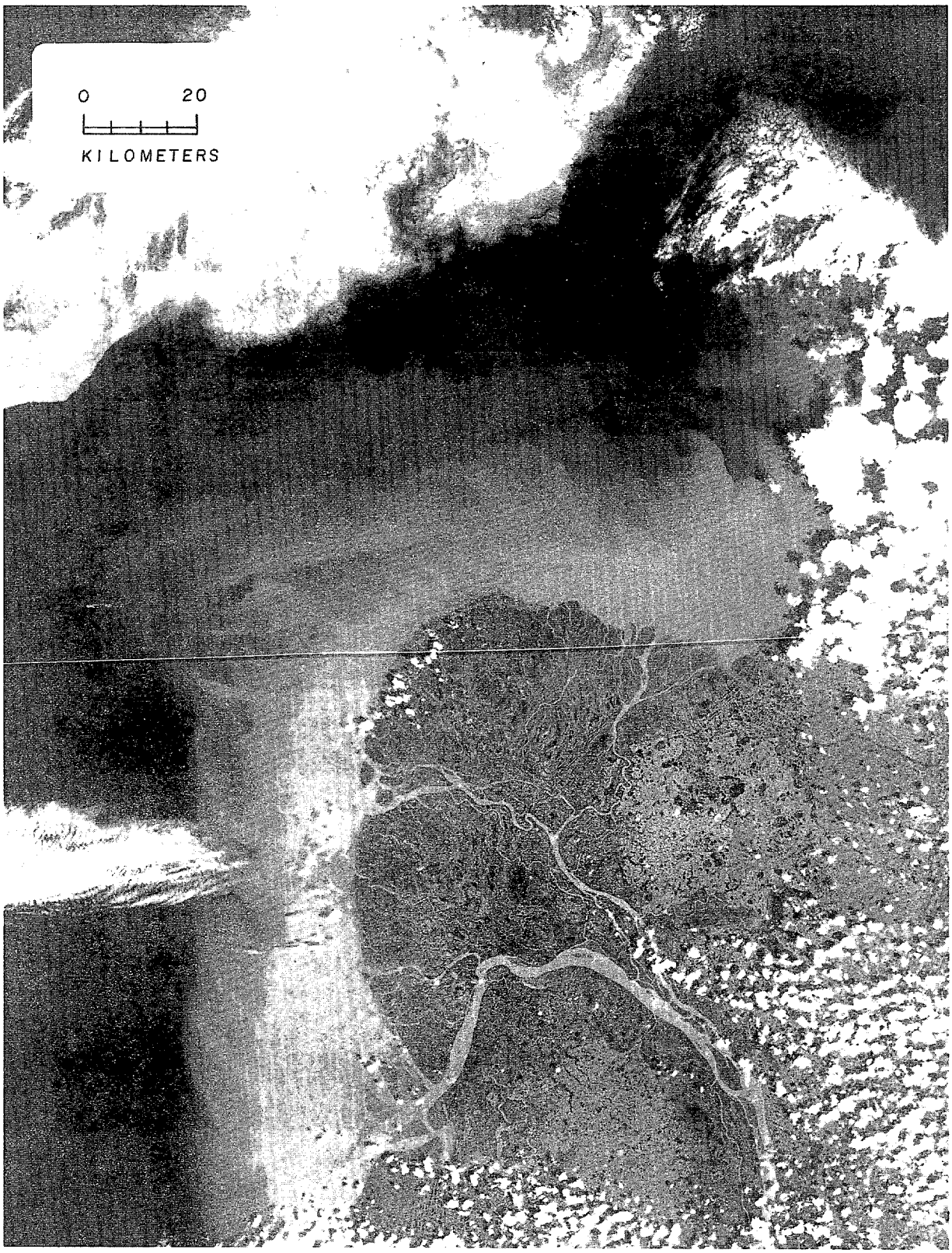

Figure 42. MSS Band 5 of LANDSAT images E-21640-21360-5 and and E–21640-21363-5 taken on 20 July 1979, showing inferred transport of suspended matter (appearing lighter in tone than the less turbid water) into Norton Sound.

The near-bottom distribution of total suspended matter (fig. 41) also indicated evidence for cyclonic movement of turbid water to the northeast along the coast. Near-bottom suspended matter concentrations were highest near the mouth of the Yukon River and in the region about 20-30 km south-southwest of Nome. The near-bottom plume just seaward of the Yukon River extended to the northeast along the coast in a manner very similar to the surface plume. The near-bottom concentrations were generally higher than surface concentrations, indicating that: (1) some fraction of the Yukon River material had settled to the near-bottom region during transit, and/or (2) a portion of the bottom sediments had been resuspended and remained in suspension.

6.4.2 Particulate Elemental Composition

In order to determine regional variations of the chemical composition of suspended material in Norton Sound, the particulate samples from the July 1979 cruise were analyzed for their major and trace element content by the methods described previously. The resulting data have been separated into five regions: Yukon River estuary with salinities less than 15 parts per thousand; Yukon River estuary with salinities between 15 and 25 parts per thousand; eastern Norton Sound; central Norton Sound; and western Norton Sound-northeastern Bering Sea Shelf. The averaged chemical data, along with published data for the Yukon River, are given in Tables 16 and 17. Table 18 shows C/N and element/Al ratios for the averaged data.

The elemental concentrations and elemental ratios illustrate some compositional differences between the suspended material discharging from the Yukon River and suspended matter in the Sound. These differences can be viewed in terms of relative aluminosilicate and organic matter percentages. Since most

of the Al in marine particulate matter is located in aluminosilicate material (Sackett and Archenius 1962), the Al concentrations in the suspended matter when multiplied by 10 can be used to estimate aluminosilicate percentages in the particulate matter. Based on the particulate Al and particulate C concentrations, the suspended matter from the Yukon River estuary was composed of approximately 88% aluminosilicate material and 6% organic matter. In like marine r, samples from eastern and central Norton Sound contain about the same percentage of aluminosilicate material (88-92%). These results illustrate the predominance of the detrital material from the Yukon River in the central and eastern regions of the Sound. This finding is additionally supported by the chemical data for Si, K, Ca, Ti, Fe, Ni, and Cu which are at about the same concentration levels in eastern and central Norton Sound and the Yukon River estuary. Only C, N, Mn, and Zn show enrichments offshore. For C and N these enrichments are attributed to a relative increase in the concentration of marine organic matter in offshore waters, which is probably due to increased light penetration away from the zone of high turbidity. This conclusion is supported by the C/N ratios (table 17) which show a general decrease seaward, indicating a transition from organic matter dominated by terrestrial material of marine origin with C/N ratios ranging between 6 and 9 (Loder and Hood, 1972). Mn and Zn enrichments can be attributed to a number of processes which are discussed in detail later.

In the western Norton Sound-northeastern Bering Sea Shelf region, the suspended matter was depleted in particulate Mg, Al, K, Ti, Fe and Ni and enriched in particulate C and N relative to the Yukon River estuarine samples. These depletions are attributed to a drop in the relative amount of aluminosilicate material in the suspended matter (< 52% by weight) and an increase in

the proportion of marine organic matter (> 40% by weight), which is depleted in Mg, Al, K, Ti, Mn, Fe, Ni and Zn relative to aluminosilicate material (Martin and Knauer, 1973). It is important to note, however, that Mn and Zn concentrations do not decrease appreciably in the samples from this region. These findings indicate that Mn and Zn concentrations in the suspended matter are controlled by distinctly different chemical processes.

In an attempt to determine the chemical nature and source of the enriched Mn and Zn in the offshore suspended matter, selected surface and near-bottom samples were treated with 25% (v/v) acetic acid to separate poorly structured oxyhydroxides from the more crystalline phases. This procedure has been shown to selectively dissolve trace elements precipitated in acid-soluble metal oxides and those adsorbed onto mineral surfaces without affecting highly oxidized ferromanganese minerals or the lattice structure of clays (Hirst and Nicholls, 1958, Chester and Hughes, 1967; and Bolger et al., 1978). The results of these experiments are given in table 18. The data show increased amounts of weak-acid-soluble Mn in the offshore samples relative to the estuarine samples, which are significant at the $p < 0.05$ level. These increases, which are computed by taking the differences between the offshore samples and estuarine samples as a ratio to the estuarine samples, range between 134% and 351% and account for all of the excess Mn in the suspended matter. Similarly, the data for Zn in the weak-acid-soluble fraction show enrichments ranging between 61% and 83% in the offshore samples which are significant at the $p < 0.20$ level. These results indicate that in the offshore waters Mn and Zn are being concentrated in the weak-acid-soluble fraction of the particulate matter, which in these samples probably consists of poorly structured oxhydroxides of Mn.

There are several possible sources for the excess Mn in the suspended matter of Norton Sound. These include: (1) differential settling of particles of various sizes; (2) resuspension of Mn-enriched sediments; and (3) reductive dissolution of Mn within recent sediments followed by oxidative precipitation of Mn onto particulate phases in the water column. The first mechanism is unlikely in view of Gibbs' (1977) data for the chemical variations in the various size fractions of Yukon River suspended material. The mean particle size distribution of suspended material in the Sound would have to decrease by about an order of magnitude (i.e., a decrease from an average size of about 20 μm to about 2 pm) before the two- to threefold increases in total Mn would be observed. Unless some unusual chemical interactions were occurring in the estuary, this would necessarily be accompanied by a similar enrichment of total Fe and Cu in the suspended matter. No enrichments of that magnitude were observed in the Fe and Cu data. Furthermore, the particle size data of Cacchione and Drake (1979) indicate that suspended matter in Norton Sound is primarily composed of fine-to-medium silt in the range between 4 and 32 pm. These data indicate that if differential settling occurs in Norton Sound, it is definitely not of the magnitude required to produce the observed Mn enrichments in the suspended matter.

The resuspension mechanism can also be refuted using a similar argument. While the suspended matter distributions indicated that bottom sediments were being resuspended, the Mn content of the bulk sediments have been reported to be only in the range between 600 and 1650 ppm (Larsen et al., in press]. This means that the Mn content of the resuspended material would have to exceed the concentration observed within the sediments by a factor of about 2-4 to account for the observed Mn concentrations in the suspended matter. This would occur only if the clay size fraction of the sediments were being preferentially

resuspended. Since the particle size data of Cacchione and Drake (1979) do not show any evidence for a decrease of this kind, this mechanism does not seem likely.

Reduction of Mn after burial in recent sediments with accompanying upward transport of dissolved Mn into the overlying water, followed by precipitation onto suspended matter best explains the observed data. Efflux of Mn from rapidly accumulating sediments have been reported for several estuarine and coastal environments (Elderfield, 1976; Graham et al., 1976; Aller, 1977; Trefry, 1977; Yeats et al., 1979; and Massoth et al., 1979). From studies of the sediments extending seaward of the Mississippi River, Trefry (1977) found that Mn fluxes from recent sediments varied directly with sedimentation rate. High Mn fluxes (i.e., ≅ 2.7 g Mn $cm^{-2}d^{-1}$) were observed in sediments that accumulate at a rate of about 2.0 g cm^{-2} y^{-1}, whereas low Mn fluxes (0.71 g Mn $cm^{-2}d^{-1}$) were observed in sediments that accumulate at a rate of 0.08 g $cm^{-2}y^{-1}$. In Norton Sound modern sediments with accumulation rates ranging from 0.05 to 0.17 g $cm^{-2}y^{-1}$ cover an area of approximately 22,000 km^2 (Nelson and Creager, 1977). Assuming an average sedimentation rate of 0.1g $cm^{-2}y^{-1}$. for these sediments and using linear interpolation of Trefry's (1977) Mn flux data (i.e., 0.68 g Mn $cm^{-2}d^{-1}$), approximately 1.5 x 108g Mn would be released daily into Norton Sound from this source. At this rate it would require approximately 21 days to account for all of the estimated excess Mn in the particulate matter (approximately 3.1 x 10^9g Mn, assuming a total area of 45,000 km^2, an average depth of 16 m, an average suspended matter concentration of 4.0 mg/L, and an average concentration of excess Mn at 1079 ppm). If it is assumed that the rate of Mn oxidation is fast relative to an accumulation time of 21 days, then contact periods approximately equal to this time

would be required for the chemical interactions to occur. While circulation in the Sound is not completely understood, studies conducted during summer indicate relatively sluggish circulation (Muench et al). Net currents, with speeds varying between 10 and 15 km d-l in surface waters and between 1 and 4 km d-l in deep water, have been measured for short periods of time. Using a mean current of 8 km d^{-1} and a mean travel distance of 400 km, it is estimated that about 50 days are required for water to pass through the Sound. This is a little more than twice the time required for the Mn from the sediment to accumulate onto the suspended matter. Thus , if the underlying assumption that the kinetic rate of Mn oxidation in coastal waters is relatively rapid is correct, then the sediments could easily be the major source of the excess Mn in the suspended matter. The assumption of a rapid rate for Mn oxidation is supported by the recent findings of Wollast et al. (1979), who found that in the Rhine and Scheldt estuaries, Mn oxidation is essentially complete within 10 days and the process is mediated by several strains of marine bacteria indigenous to coastal environments.

The preceding discussion about the geochemical behavior of Mn in the Sound is also important for understanding the chemical behavior of Zn in the suspended matter. As noted earlier, both Zn and Mn are enriched in the weak-acid-soluble fraction of the particulate matter. This is probably due to adsorption and/or coprecipitation of Zn on or in the newly formed Mn oxyhydroxides. Figure 43 shows a plot of the relationship between total Zn and total Mn and for both surface and near-bottom samples. The plot of total Zn versus total Mn is roughly linear (r = 0.60) indicating an association between these two metals in the particulate matter. These results suggest that as the Mn oxyhydroxides form on the particulate matter, Zn is scavenged from solution. In similar fashion, the relationship between weak-acid-soluble Zn and weak-

acid-soluble Mn is also roughly linear (r = 0.39). This process effectively concentrates Zn and Mn in the suspended matter, which eventually either settles to the bottom of the Sound or is transported to the northwest into north-eastern Bering Sea Shelf and beyond.

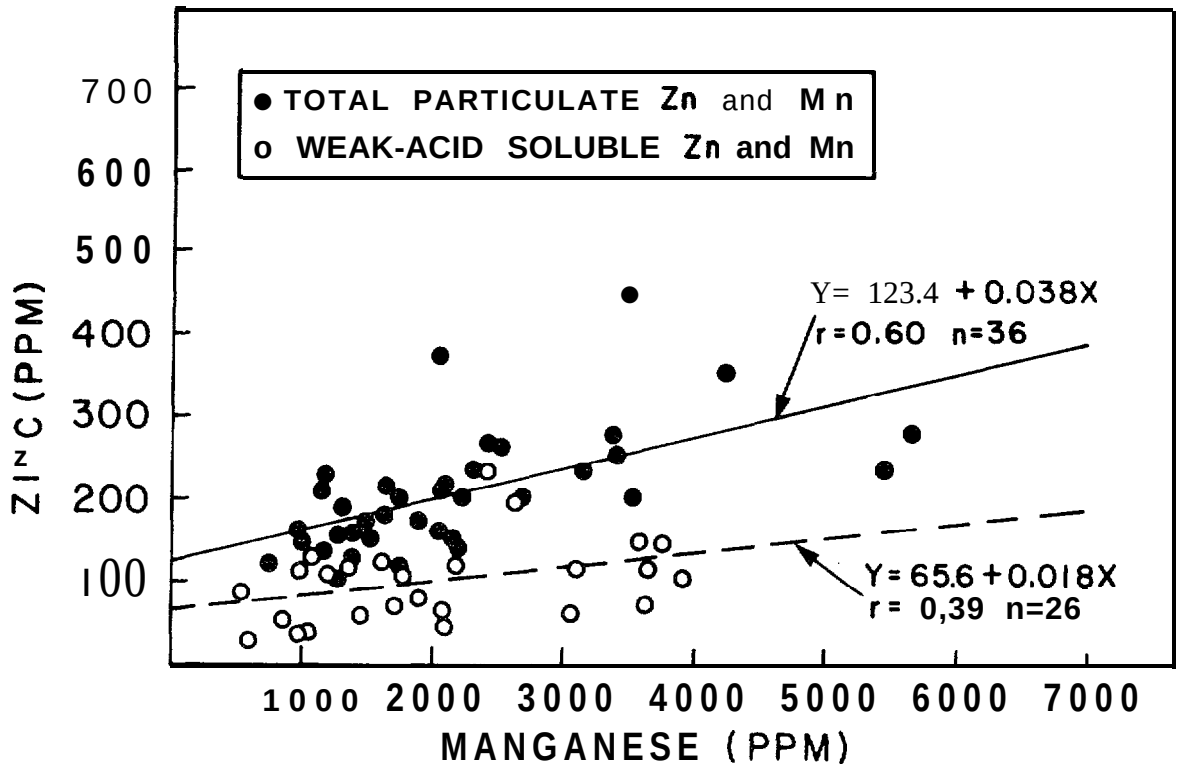

Figure 43. **Scatter plot of the relationships between total particulate Zn and Mn (●) and weak-acid soluble Zn and Mn (○) in suspended matter from Norton Sound.**

TABLE 16. Comparison of the elemental composition of suspended material from the Yukon River with the composition of suspended ❑aterial collected from the near-shore regions seaward of the mouths of Yukon River distributaries (surface samples collected with precleaned polyethylene bottles, 11-12 JuIy 1979). Standard deviations are given only for data obtained during a single sampling event wherever applicable.

Sample Ascription	No. of Samples	C†† wt. % ± 1σ	N†† wt. % ± 1σ	Mg wt. % ± 1σ	Al wt. % ± 1σ	Si wt. % ± 1σ	K wt. % ± 1σ	Ca wt. % ± 1σ	Ti wt. % ± 1σ	Cr ppm ±1σ	Mn ppm ±1σ	Fe Wt. % ± 1σ	Ni ppm ±1σ	Cu ppm ±1σ	Zn ppm ±1σ
Yukon River Suspended Material															
Yukon River at Klakanak*										147	1079	5.4	109	320	
Yukon River at Pilot Station**		0.24-3.8								48	788-1308	3.1-4.3		24-148	49-142
Yukon River Estuary															
Surface Samples (0-150/₀₀)	6	2.9 ±0.6	0.2 ±0.04	2.3 ±0.7	8.3 ±1.3	30.6 ±1.9	2.2 ±0.3	1.5 ±0.2	0.50 ±0.06	110 ±15	992 ±131	5.5 ±0.8	59 ±8	59 ±8	171 ±49
Yukon River Estuarv															
Surface Samples (15-25°/00)	6	4.2 ±1.2	0.4 ±0.8	3.1 ±0.8	9.3 ±1.8	31.5 ±3.7	2 . 1 ±0.2	1.6 ±0.2	0.52 ±0.03	129 ±15	1299 ±192	5.8 ±0.4	60 ±5	61 ±10	193 ±30

*Data from Gibbs (1977)

**Water Resources Data (1976-1977) U.S. Geological Survey

††Weight percentages of C and N were determined using two different filter types (Selas® silver filters and Nuclepore® filters) and, therefore, are subject to a greater number of errors than the data obtained for the inorganic elements, which were obtained from a single filter type.

TABLE 17. Summary of the elemental composition of suspended material collected from selected locations in Norton Sound and northeastern Bering Sea Shelf (samples were collected with 10-L Niskin bottles, 7-18 July 1979).

Sample Description	No. of Samples	C†† wt. % ± 1σ	N†† wt. % ± 1σ	Mg wt. % ± 1σ	Al Wt. % ± 1σ	Si wt. % ± 1σ	K wt. % ± 1σ	Ca wt. % ± 1σ	Ti wt. % ± 1σ	Cr ppm ±1σ	Mn ppm ±1σ	Fe wt. % ± 1σ	Ni ppm ±1σ	Cu ppm ±1σ	Zn ppm ±1σ
Eastern Norton Sound															
Surface	7	15.4 ±4.8	2.4 ±0.9	3.1 ±0.5	9.2 ±1.4	30.1 ±3.7	1.7 ±0.3	1.4 ±0.3	0.44 ±0.06	199 ±59	2346 ±845	5.3 ±0.6	52 ±8	60 ±9	201 ±41
5 m Above Bottom	7	10.1 ±6.2	1.1 ±0.8	2.9 ±0.5	9.1 ±1.3	31.0 ±2.7	2.0 ±0.2	1.4 ±0.2	0.53 ±0.08	144 ±38	2182 ±682	5.7 ±0.4	57 ±5	62 ±10	276 ±289
Central Norton Sound															
Surface	18	14.6 ±8.6	1.9 ±1.1	3.3 ±0.7	9.0 ±1.7	30.8 ±4.8	1.7 ±0.4	1.7 ±0.2	0.48 ±0.08	148 ±36	2672 ±1104	5.4 ±0.8	59 ±21	61 ±12	246 ±90
5 m Above Bottom	18	5.6 ±3.6	0.7 ±0.5	3.0 ±0.6	8.8 ±1.2	32.4 ±2.5	2.0 ±0.2	1.6 ±0.6	0.54 ±0.06	138 ±27	1797 ±287	5.8 ±0.6	57 ±7	58 ±6	196 ±65
Western Norton Sound-northeastern-Bering Sea Shelf															
Surface	18	25.6 ±6.8	4.0 ±0.9	0.9 ±0.7	3.2 ±1.4	20.0 ±7.9	0.5 ±0.2	1.4 ±0.4	0.23 ±0.10	100 ±93	2160 ±1392	2.3 ±0.9	29 ±17	50 ±39	194 ±111
5 m Above Bottom	18	12.3 ±6.9	1.3 ±0.4	1.9 ±0.5	5.1 ±1.2	31.8 ±3.5	0.9 ±0.3	1.2 ±0.2	0.31 ±0.07	81 ±17	1506 ±761	3.4 ±0.7	30 ±13	36 ±11	137 ±60

†† Weight percentages of C and N were determined using two different filter types (Selas® silver filters and Nuclepore® filters) and, therefore, are subject to a greater number of errors than the data obtained for the inorganic elements, which were obtained from a single filter type.

TABLE 18. Average C/N and Element/Al ratios for suspended materials from the Yukon River Estuary, Norton Sound and northeastern Bering Sea Shelf.

Sample Description	C/N	C/Al	N/Al	Mg/Al	Si/Al	K/Al	Ca/Al	Ti/Al	Cr/Al x10-3	Mn/Al x10-3	Fe/Al	Ni/Al x10-3	Cu/Al x10-3	Zn/Al x10-3
Yukon River Estuary (0-150/00)	14.5	0.35	0.02	0.28	3.73	0.27	0.18	0.06	1.34	12.1	0.66	0.72	0.72	2.08
Yukon River Estuary (15-25°/00)	10.5	0.45	0.04	0.33	3.39	0.23	0.17	0.06	1.38	14.0	0.62	0.64	0.66	2.07
Eastern Norton Sound														
Surface	6.4	1.71	0.27	0.34	3.34	0.19	0.16	0.05	2.21	26.1	0.59	0.58	0.66	2.23
5 m Above Bottom	9.2	1.11	0.12	0.32	3.41	0.22	0.15	0.06	1.58	24.0	0.63	0.63	0.68	3.03
Central Norton Sound														
Surface	7.7	1.62	0.21	0.37	3.42	0.19	0.19	0.05	1.64	29.7	0.60	0.65	0.67	2.73
5 m Above Bottom	8.0	0.63	0.08	0.34	3.68	0.23	0.18	0.06	1.57	20.4	0.66	0.65	0.66	2.23
Western Norton Sound-Northeastern Bering See Shelf														
Surface	6.4	8.0	1.30	0.28	6.35	0.16	0.44	0.07	3.12	67.5	0.72	0.91	1.56	6.06
5 m Above Bottom	9.5	2.4	0.25	0.37	6.23	0.17	0.24	0.06	1.59	29.5	0.66	0.59	0.67	2.68

TABLE 19. Partitioning of Mn and Zn between weak-acid-soluble (WAS) and weak-acid-insoluble (WAI) fractions of suspended material from Norton Sound and northeastern Bering Sea (data presented as a percentage of total suspended matter).

Sample Location	No. of Samples	WAS Mn ±1σ	WAI Mn ±1σ	WAS Zn ±1σ	WAI Zn ±1σ
Yukon River Estuary	3	0.066 ±0.017	0.052 ±0. 006	0.0059 ±0 .0028	0.0140 ±0.0031
Eastern Norton Sound	5	0.155 ±0.038	0.040 ±0.011	0.0095 ±0. 0031	0.0099 ±0. 0021
Central Norton Sound	9	0.184 ±0 .085	0.054 ±0.017	0.0108 ±0 .0056	0.0114 ±0.0026
Western Norton Sound	9	0.298 ±0.092	0.074 ±0.041	0.0107 ±0.0053	0.0125 ±0.0070

i'. CONCLUSIONS

7.1 Northeast Gulf of Alaska

The most significant conclusions of the particulate matter studies in the northeastern Gulf of Alaska are listed below:

1. The distribution of suspended matter at the surface appear to follow the general pattern of water circulation in the Gulf. East of Kayak Island sedimentary material, which is discharged along the coast, is quickly deflected to the west by coastal currents. This material is deflected to the southwest near Kayak Island and is trapped by a clockwise gyre.

2. Sedimentary material from the Copper River is carried to the northwest along the coast until it reaches Hinchinbrook Island where a portion of the material passes into Prince William Sound and the remaining material is carried to the southwest along the southeastern coast of Montague Island.

3. Comparisons of surface suspended matter distribution maps for the three cruises in the Gulf show significant variations which can be related to seasonal variations in the discharge of terrestrially derived suspended matter, seasonal variations in primary productivity, and occasional offshore transport of suspended matter by wind-generated eddies.

4. A bottom nepheloid layer is present throughout most of the Gulf. The height of the nepheloid layer appears to be dependent upon the bottom topography and local currents. Studies of the temporal variability of suspended matter near the bottom show evidence for resuspension and redistribution of bottom sediments. These processes occur as a result of interactions between tidal and storm-induced bottom currents and the surficial sediments.

5. Studies of the chemical composition of the suspended matter show significant spatial and seasonal variations. These variations have been

correlated with: (1) seasonal variations in primary production; (2) seasonal variations in the supply and transport of terrestrially derived suspended matter from coastal rivers; and (3) resuspension of bottom sediments.

7.2 Lower Cook Inlet and Shelikof Strait

The most significant findings of the suspended matter program in lower Cook Inlet are listed below.

1. The suspended matter distributions appear to follow the general pattern of circulation in lower Cook Inlet and Shelikof Strait. The inflowing relatively clear Gulf of Alaska water, which contains significant amounts of biogenic particles as well as aluminosilicate material from the Copper River, flows northward along the eastern coast until it reaches Cape Ninilchik, where it mixes with the outflowing turbid brackish water. The outflowing turbid water moves along the western side of the inlet past Augustine Island and Cape Douglas into Shelikof Strait where it mixes with the oceanic water and is dispersed. Comparison of suspended matter and sediment characteristics as well as regional sedimentation rates indicates that net sedimentation of suspended matter in the central basin of lower Cook Inlet is minimal. However, net sedimentation is occurring in the embayments along the coast and in Shelikof Strait.

2. Chemical analysis of the suspended material from lower Cook Inlet reveals that aluminosilicate minerals from the coastal rivers comprise about 80-95% of the suspended matter, with biogenic matter making up the rest. Analysis of seasonal and regional variations of C/N ratios indicates that organic matter of marine origin predominates the eastern part of lower Cook Inlet throughout the year, whereas organic matter of terrestrial origin predominates the western part of the inlet during winter and early spring when primary production is at a minimum.

3. Comparisons of regional average concentrations of major and trace elements in the particulate matter indicate regional differences which can be related to differences in the average composition of source material and the relative amounts of biogenic and terrigenous components.

4. Studies of trace metal associations with particulate matter reveal that: (1) Mn, Cu, and Zn are enriched in the organic phase of suspended matter in surface waters of Kachemak Bay; and (2) the weak acid soluble phase contains about 46-99% of the total Cu, Ni, and Zn in the samples from the Kalgin Island region. These differences are attributed to differences in the sources for the particles, with primary production of biogenic particles predominant in Kachemak Bay and river discharge of terrestrial rock debris predominant in the Kalgin Island region.

5. Studies of sediment accumulation rates in lower Cook Inlet indicate that most of the suspended material discharged from the local rivers is deposited in Shelikof Strait, not in Cook Inlet. This finding is important for understanding and predicting the long-term fates of contaminants associated with suspended matter.

7.3 Southeastern Bering Sea Shelf

The most significant conclusions of the suspended matter program in the southeastern Bering Shelf are listed below.

1. The surface suspended matter distributions appear to follow the general pattern of circulation in Bristol Bay. Terrestrial suspended matter from the northern rivers is generally carried to the west and southwest by the counterclockwise currents.

2. Large plumes of suspended matter can be seen extending to the southwest from Cape Newenham and to the west from Kuskokwim Bay. Apparently these plumes represent sedimentary material derived from the Kvichak, Nushagak, and Kuskokwim Rivers.

3. Suspended material of marine origin is carried into Bristol Bay along the northern coast of the Alaska Peninsula. In the region north of Unimak Pass large suspended matter plumes have been observed in the early summer and are apparently the result of seasonal productivity.

4. Sharp increases in suspended matter concentrations near the bottom indicate that resuspension of bottom sediments is occurring.

7.4 Norton Sound

The most significant findings of the suspended matter program in Norton Sound are listed below.

1. The suspended matter distribution appears to follow the general pattern of cyclonic circulation in the Sound. The inflowing water picks up terrigenous aluminosilicate material from the Yukon River and transports it to the north and northeast around the inside periphery of the Sound, with one-half to two-thirds of the material being deposited as a band of sediments extending from the Yukon River Delta northward and eastward and the remaining material being transported to the northwest through the Bering Strait and deposited in the Chukchi Sea.

2. Chemical analysis of the suspended material from Norton Sound reveals that aluminosilicate material from the Yukon River comprises about 88-92% of the suspended matter, with biogenic matter making up the rest. Analysis of regional variations of C/N ratios indicates that organic matter of marine

origin predominates in Norton Sound basin, whereas organic matter of terrestrial origin predominates in the Yukon River Estuary.

3. Comparisons of regional average concentrations of major and trace elements in the particulate matter indicate regional differences which can be attributed to differences in the average composition of source material and the relative amounts of biogenic and terrigenous components.

4. **Studies of trace metal associations with particulate matter reveal that Mn and Zn are enriched in an oxyhydroxide phase of the surface and near-bottom suspended matter in Norton Sound.**

8. Publications and Presentations

Following is a list of publications and presentations that have resulted from this research unit:

Feely, R. A. and G. J. Massoth (in press). Sources, composition, and transport of suspended particulate matter in lower Cook inlet and northwestern Shelikof Strait, Alaska, U. S. Geological Survey Professional Paper.

Feely, R. A., G. J. Massoth, and A. J. Paulson (1981). The distribution and elemental composition of suspended particulate matter in Norton Sound and the northeastern Bering Sea Shelf: implication for Mn and Zn recycling in coastal waters. In: The Eastern Bering Sea Shelf: Oceanography and Resources, D. W. Hood and J. A. Calder (eds.), Vol I pp. 321-338. U.S. Dept. of Commerce, Washington, D.C.

Feely, R. A., A. J. Chester, A. J. Paulson, and J. D. Larrance (in press). Relationships between organically bound Cu and Mn in settling particulate matter and biological processes in a subarctic estuary, Estuaries.

Landing, W. M., and R. A. Feely (1981). Major and trace element distributions among vertically settling particles and underlying sediments from the northeast Gulf of Alaska, Deep-Sea Res. 28A: 19-37.

Feely, R. A., G. J. Massoth and W. M. Landing. Major and trace element composition of suspended matter in the northeast Gulf of Alaska: Relationships with major sources, submitted to Marine Chem.

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